Some Revised Observational Constraints on the Formation and Evolution of the Galactic Disk

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ABSTRACT

A set of 76 open clusters with abundances based upon DDO photometry and/or moderate dispersion spectroscopy has been transformed to a common metallicity scale and used to study the local structure and evolution of the galactic disk. The metallicity distribution of clusters with galactocentric distance is best described by two distinct zones. Between R_{GC} = 6.5 and 10 kpc, the metallicity distribution has a mean [Fe/H] = 0.0 and a dispersion of 0.1 dex; there is, at best, weak evidence for a shallow abundance gradient over this distance range. Beyond R_{GC} = 10 kpc, the metallicity distribution has a dispersion between 0.10 and 0.15 dex, but with a mean [Fe/H] = –0.3, implying a sharp discontinuity at R_{GC} = 10 kpc. After correcting for the discontinuity, no evidence is found for a gradient perpendicular to the plane. Adopting the clusters interior to 10 kpc as a representative sample of the galactic disk over the last 7 Gyr, the cluster metallicity range is found to be approximately half that of the field star distribution. When coupled with the discontinuity in the galactocentric gradient, the discrepancy in the metallicity distribution is interpreted as an indication of significant diffusion of field stars into the solar neighborhood from beyond 10 kpc. These results imply that, contrary to earlier claims, the sun is **not** atypical of the stars formed in the solar circle 4.6 Gyr ago. It is suggested that the discontinuity is a reflection of the edge of the initial galactic disk as defined by the disk globular cluster system and the so-called thick disk; the initial offset in [Fe/H] created by the differences in the chemical history on either side of the discontinuity has been carried through to the current stage of galactic evolution. If correct, diffusion coupled with the absence of an abundance gradient could make the separation of field stars on the basis of galactocentric origin difficult, if not impossible.

1. Introduction

As probes of galactic structure and evolution, open clusters have proven to be valuable but limited. Their value lies in the improvement in accuracy for distance determination, metal content, and age produced by the collective stellar sample which shares these properties. The limitations have arisen because of their often sparse population of members, age restrictions imposed primarily by tidal disruption, and the need to study an extended region of the galaxy to obtain a statistically significant sample. Despite these limitations, there has been increasing interest in the cluster population, particularly the older clusters, spurred on in recent years by the availability of CCD cameras on telescopes of modest size. The sample growth has led to a comparable growth in the analysis of its composite properties as detailed in Janes & Adler (1982), Friel (1989), Janes & Phelps (1994), Phelps *et al.* (1994), Carraro & Chiosi (1994), Friel (1995), and Scott *et al.* (1995), among others.

Despite the improvements, there are two areas where our understanding of the cluster sample has changed little in the last 15 years. Among open clusters there is no evidence for an age-metallicity relation (AMR), though a significant range in [Fe/H] exists among clusters older than 1 Gyr, as first detailed in Hirshfeld *et al.* (1978). When combined with the seminal study of the cluster galactic abundance gradient by Janes (1979), it is apparent that position within the galaxy plays a more critical role in defining a cluster's properties than age. Though subsequent estimates for the cluster abundance gradient have often been somewhat steeper than the original Janes (1979) value, the basic result that the outer galactic disk is metal-poor relative to the inner disk has been confirmed many times since, in particularly conclusive fashion by Friel & Janes (1993), supplemented by Thogersen *et al.* (1994; hereafter collectively referred to as FJ).

More recently an even larger sample has been used by Piatti *et al.* (1995; hereinafter PCA) to derive a similar galactocentric abundance gradient and, for the first time, an open cluster abundance gradient perpendicular to the galactic plane, contradicting the conclusions of FJ. The unique nature of the latter result combined with a revised calibration of the DDO system (Twarog & Anthony-Twarog 1996), the photometric system adopted by PCA, suggested the need for a closer look at the cluster sample and the reality of the Z-gradient, where Z refers to the direction perpendicular to the plane. We find that the commonly accepted picture of a linear abundance gradient with galactocentric distance (R_{GC}) coupled with a large spread in abundance at a given age in the solar neighborhood fails to account for the observations. Instead, the disk breaks up into two distinct populations defined by a sharp boundary at $R_{GC} = 10$ kpc. The goals of this paper are to explain the changes in the cluster analysis which are the foundation of the new sample (Sec. 2), to quantify the reality of the two cluster populations and the galactic abundance gradient (Sec. 3), to compare

and contrast the cluster population with that of the field stars in the solar neighborhood, and to attempt an explanation of the source of the apparent discrepancy between the field stars and the clusters (Sec. 4). Our conclusions and a qualitative scenario for the evolution of the disk are summarized in Sec. 5.

2. The Data

Two key cluster parameters of interest are metallicity and the distance. Given these and galactic position, one can construct a spatial map of the cluster population and study its global characteristics. The number of clusters for which metallicity estimates exist is well over a hundred, but such estimates involve an array of techniques used by different observers with differing choices for cluster membership, reddening, and abundance calibrations. Simple merger of all cluster abundances can wash out or destroy detailed structure within the cluster population unless it is done with extreme care. We will make use of only two sources, the DDO sample described in PCA and the spectroscopic sample in FJ. We have excluded the unpublished abundances listed in Friel (1995) and the supplemental data of Lyngå (1987) used by FJ and Friel (1995) because many of the clusters contained in the supplemental sample have DDO data and, in key cases, the parameters found in Lyngå (1987) have proven to be unreliable.

2.1. Reddening and Distance Estimation

The first step in the cluster compilation is the determination of cluster reddening. No single technique for reddening estimation has been applied to all the clusters in the sample, though the DDO - $(B-V)$ technique of Janes (1977b) is applicable to a large fraction. We have surveyed the literature for each cluster, attempting to assess the range and reliability of the published values. In the end we have adopted a representative estimate for each cluster. To make the most effective use of the reddening determinations we have included an adjustment which is often neglected in cluster analyses. It has been known since the work of Lindholm (1957) and Schmidt-Kaler (1961) that the degree of reddening experienced by a star is dependent upon the color of the star. Generally, a red giant exhibits a smaller $E(B-V)$ than a hotter main sequence star when obscured by the same dust layer. Fernie (1963) has calculated that a change in the intrinsic $(B-V)$ of 1.0 mag lowers the effective $E(B-V)$ by approximately 10%. One of the few discussions and applications of this phenomenon can be found in Hartwick & McClure (1972). In deriving the reddening appropriate for a cluster, we have taken into account whether or not the estimate is based

on the giants or hotter stars near the turnoff. Final values are adopted individually for the main sequence and the giant branch, fixed to ensure consistency based upon their relative colors. The typical difference in $E(B-V)$ lies in the 5% to 10% range, leading to a minor difference for the majority of clusters which have $E(B-V)$ below 0.10. Details for the individual clusters may be found in the Appendix. In a majority of the cases our results differ little from those listed in PCA and FJ, though controversy still surrounds a number of key objects, e.g., NGC 6791.

The grab-bag approach to reddening may, at first glance, appear to violate the concern expressed above regarding the merger of abundances. However, one of the strengths of both metallicity techniques and one of the key reasons they were selected for this sample is their weak sensitivity to reddening changes. For a change in $E(B-V)$ of 0.1 mag, the corresponding change in [Fe/H] is between 0.10 and 0.15 for the photometric and the spectroscopic (Friel 1997) approaches. Clusters for which the uncertainty in the adopted reddening is larger than this have been excluded from the discussion.

Reddening values, though not critical to [Fe/H] because of the weak sensitivity to changes in $E(B-V)$, can have a significant impact on the cluster distance. However, the effect on distance depends on the technique used in obtaining the distance. For the current investigation, three approaches have been used.

First, whenever adequate BV photometry is available, distances have been derived via main sequence fitting. As a tie-in to past work, the location of the main sequence for a cluster of a given [Fe/H] is taken from the VandenBerg (1985) isochrones, adjusted to guarantee that a solar mass star of age 4.6 Gyr with solar composition has the adopted $(B-V)$ of 0.65 and $M_V = 4.84$ (Twarog & Anthony-Twarog 1989). Differential corrections to the distance due to differences between the cluster [Fe/H] and that of the nearest isochrone set are applied using the metallicity dependence as described in VandenBerg & Poll (1989).

For the effect of reddening on distance determination via main sequence fitting, two factors compete. Increased reddening correction moves the main sequence toward the blue. If the slope of the main sequence with $(B-V)$ is X, the apparent modulus is increased by X$*E(B-V)$. However, corrections to the distance modulus for increased reddening make the true modulus smaller. The net change in the true modulus is (X − 3.1)$*E(B-V)$. For the unevolved, cooler main sequence, X is between 5 and 6. From the base of the turnoff, X rapidly increases, reaching above 10 as the turnoff approaches vertical, or for the hotter main sequence of younger open clusters. Ideally, one would prefer to use the cooler, unevolved main sequence to derive distances, but this is not always possible. Main sequence fitting was applied to 49 clusters.

Second, for some older (>1.0 Gyr) clusters, the main sequence is too faint or too ill-defined to permit reliable fits. If it can be identified, however, the red giant clump provides an adequate method of estimating the distance. Using 13 clusters with well-defined main sequences and red giant clumps, we have derived the typical M_V for the clump using main sequence fitting. Assumed reddenings and abundances are taken from Table 1. As illustrated in Fig. 1a, there is a weak dependence on metallicity, predominantly caused by the most metal-rich cluster in the sample, NGC 6791. In Fig. 1b, the dependence on age is investigated. Rather than adopt an absolute age scale and become involved in the controversy which often surrounds such choices, we have instead used an age ranking based upon the morphological cmd parameter, MAR, as defined in Anthony-Twarog & Twarog (1985) and revised in Twarog & Anthony-Twarog (1989). The MAR is a ratio of the magnitude difference between the red giant clump and the brightest point at the turnoff to the color difference between the red giant branch at the level of the clump and the bluest point of the turnoff. Combining both parameters enhances the age sensitivity while partially removing the metallicity sensitivity of the cmd morphology. The ratio should also be reddening-independent, but this assumption fails for clusters with large $E(B-V)$ due to the reddening dependence on stellar color. To allow readers to place the trend in Fig. 1b on their preferred age scale, we have tagged a few of the extreme clusters. The youngest objects are NGC 7789 and NGC 3680, while the oldest are M67, MEL 66, NGC 188, BE 39, and NGC 6791.

Over the age range from NGC 7789 to MEL 66 (approximately 1 to 5 Gyr), the mean M_V is 0.6 ± 0.1; the scatter is explained by the uncertainties in the distance moduli and in the exact definition of the clump. We have attempted to choose the latter parameter based upon the magnitude which is typical of the average star in the clump, rather than the reddest or bluest point. From MEL 66 to NGC 6791 (approximately 5 Gyr to 9 Gyr), the M_V declines from 0.6 to 1.2 for NGC 6791. The fact that NGC 6791 has both the largest age and the largest [Fe/H] makes it impossible to decouple the effects of age and metallicity on M_V among the oldest clusters, though it does appear likely comparing Figs. 1a and 1b that age is the predominant effect in the increase in M_V.

For most clusters in the age range of 1 Gyr to 5 Gyr, we will adopt $M_V = 0.6$ for the clump. For metal-rich and/or significantly older clusters, we will adopt a value between 0.7 and 1.0. The specifics for each cluster can be found in the Appendix. We note in closing that Janes & Phelps (1994) have attempted a similar estimate of the clump luminosity, deriving $M_V = 0.90 \pm 0.40$ from 23 clusters older than 1 Gyr. The difference is easily explained. The cluster sample used by Janes & Phelps (1994) is a composite from a wide variety of sources. Distance moduli depend upon reddening, metallicity, and the adopted main sequence for the fit. The lack of normalization among the various observers,

particularly in isochrone fits from different theoretical models, is a primary source of both the large scatter and the fainter M_V. Second, the abundances for the clusters discussed in Figs. 1a and 1b are generally higher than found in past discussions of the clusters, particularly those in the galactic anticenter. A larger [Fe/H] leads to a larger modulus for a given main-sequence fit. The red giant clump was used to derive distances for 4 clusters.

For cluster distances derived by fitting the red giant clump to a fixed M_V, the apparent modulus is fixed by the apparent brightness of the clump. Changing $E(B-V)$ alters the true modulus by $A_V = 3.1{*}E(B-V)$, making it smaller as $E(B-V)$ grows larger.

Third, if neither main sequence fitting nor a red giant clump match are plausible means of deriving $(m-M)$, any technique available in the literature is used. In most cases, this implies a distance determination tied to a photometric M_V calibration using intermediate or broad-band photometry of the giants, as in DDO, or main sequence stars, as in $uvby$Hβ. The exact impact on the distance estimate of changing the reddening is unique to each photometric system. This approach was adopted for 23 clusters.

As a prelude to the discussion in Sec. 3, we point out that estimation of the uncertainties in the distance moduli is not trivial. Even for a given approach, not all distances derived with that method will have equal errors when using an amalgam of data sources. Though we have taken the coward's way out and used the same uncertainty, ±0.2, for all the moduli, the conclusions of the investigation are only weakly dependent upon uncertainties in the moduli. For main sequence fitting, in a differential sense, the best cluster data are estimated to provide moduli with an uncertainty between ±0.1 and ±0.2 mag; the same number applies to the clump-based distances. For the weaker main sequence data and the majority of the distances based upon other, primarily photometric, techniques, the uncertainties are closer to ±0.3 mag, and may be larger in extreme cases. However, because the uncertainty in the distance modulus produces a percentage change in the absolute distance and the absolute error projects into a smaller change in galactocentric distance, for clusters within 2 kpc of the sun doubling the estimated uncertainty will have little impact on our conclusions.

2.2. Metallicity Estimation

Ideally, one would prefer to discuss only abundances based upon one technique and obtained by one observer. Since this is impossible we make use of two samples, one photometric on a common system, DDO, and one spectroscopic but observed by only one group. Even given only two techniques, it is still important that the abundances from each

are on a common scale. The following sections will define the metallicity scale and the means of standardizing the results.

2.2.1. DDO Photometry

The commonly adopted calibration of the δCN index of the DDO system for disk giants was first proposed by Janes (1975) based upon 44 stars. Since that time, suggested changes in the zero-point have been made by Deming *et al.* (1977) and Twarog (1981), while Luck (1991) revised both the slope and the zero-point. Piatti *et al.* (1993) revised the definition of the CN-index, using an expanded sample of 82 G and K giants to redefine the DDO metallicity calibration in terms of ΔCN, the technique applied to the open clusters in PCA. Beyond the modest sample size, the primary shortcoming of the earlier recalibrations tied to spectroscopic abundances is the lack of consistency among the sources for the spectroscopic abundances. This weakness was corrected in the comprehensive approach of Taylor (1991), using over 300 field giants adjusted to a well-defined, standardized system. Taylor (1991) concluded that the transformation of the traditional δCN index to [Fe/H] required both a slope and zero-point which were temperature-dependent.

The calibration adopted here is detailed in Twarog & Anthony-Twarog (1996). Rather than use a composite catalog of spectroscopic abundances, the DDO calibration was tied solely to the data of McWilliam (1990), a sample of 671 field giants reduced and analyzed in a uniform way. From 438 giants, Twarog & Anthony-Twarog (1996) confirmed the color dependence of the calibration zero-point, but found a constant and shallower slope than Janes (1975). It should be emphasized that the Taylor (1991) and Twarog & Anthony-Twarog (1996) calibrations, except for a small zero-point shift to approximate a Hyades abundance of [Fe/H] = +0.12, give very similar results. The use of a more internally consistent spectroscopic sample does halve the scatter in the residuals attributable to the DDO calibration, photometric errors aside, to less than ±0.05 for the bright star photometric sample of McClure & Forrester (1981). The revised calibration is applicable from [Fe/H] = +0.25 to –0.5. At lower abundances, the sample of McWilliam (1990) is inadequate to allow a reliable calibration, but use of an expanded sample shows that the calibration cannot be extrapolated. The δCN index increasingly overestimates the abundance of more metal-deficient giants (Twarog & Anthony-Twarog 1996).

For each cluster in the final sample of PCA, DDO photometry was collected using the references cited by PCA, and expanded whenever possible by doing an updated search of the literature. An analogous approach was applied to the reddening, radial-velocity data, and proper-motion studies. Definite non-members were eliminated from the sample, but

stars with no membership information were included, as were stars classed as binaries, unless otherwise noted in the Appendix. The reason for this is that a large fraction of the clusters lack definitive membership information and no binary classifications. Inclusion of these stars in the mean metallicity estimate for clusters with partial information places all the clusters on an equal footing. Moreover, it was found that exclusion of binaries rarely had a significant impact upon the mean abundance or the dispersion for a cluster.

Comparison of the results for individual clusters with those of PCA will occasionally show differences in the number of stars included in the cluster average. These differences are sometimes attributable to different calibration limits for the two techniques, but often arise because of differences in membership classification. Because PCA does not provide specific details on which stars in each cluster are excluded, we have no means of making an exact comparison. This problem is compounded by the inclusion of unpublished radial-velocity data in deciding membership.

In a few extreme cases, the cluster abundances in PCA are based exclusively upon unpublished photometry. Rather than drop these clusters from the sample, we have attempted a simple transformation of the PCA abundances to our system in the following manner. For clusters where the number of giants is large enough that small differences in the total included have little impact on the cluster mean or where no difference exists in the sample of giants included, the DDO metallicity has been calculated using the calibration discussed above and compared with that listed by PCA. To isolate the impact of the different calibrations, for this comparison we have adopted the same $E(B-V)$ as PCA for each cluster. The residuals in [Fe/H] in the sense (PCA – TAT) are plotted in Fig. 2 as a function of the [Fe/H] in PCA (open circles). The scatter at a given [Fe/H] is encouragingly small and is primarily caused by small differences in the calibrations as a function of the color of the giant. For clusters with [Fe/H] below –0.2 on the system of PCA, there appears to be a common offset of about 0.1 dex between the two metallicity scales, with that of PCA being more metal-poor. At higher metallicity, the residuals show an approximately linear trend with increasing [Fe/H], implying that the metallicity range among clusters on the scale of PCA is larger than that found on the revised scale. Based upon Fig. 2, we can transform an abundances of PCA to the approximate scale of the revised calibration using the following relations:

$$[\mathrm{Fe/H}]_{PCA} \leq -0.15 \qquad [\mathrm{Fe/H}]_{TAT} = [\mathrm{Fe/H}]_{PCA} + 0.09$$

$$[\mathrm{Fe/H}]_{PCA} > -0.15 \qquad [\mathrm{Fe/H}]_{TAT} = 0.55[\mathrm{Fe/H}]_{PCA} + 0.02$$

These transformations have been used only for clusters where the DDO photometry remains unpublished. In all other cases the DDO calibration of Twarog & Anthony-Twarog

(1996) has been applied individually to the giants.

2.2.2. *Spectroscopy*

Moderate-resolution spectra of cluster giants have been collected and calibrated by Friel and her coworkers over the last decade; the results are summarized in FJ. The beauty of the approach is that in addition to metallicity, one obtains an indication of membership via radial velocities of modest accuracy. Though the emphasis of the sample is on older disk clusters, a related byproduct is inclusion of the largest sample of abundances for clusters at large galactocentric distances, the majority of which have no DDO estimate due to the faintness of the giants.

The current DDO sample has an overlap of 14 clusters with FJ. As with the DDO sample, the literature on each cluster has been reviewed to eliminate non-members and revise the reddening estimate whenever necessary. Because the techniques of PCA and FJ make use of many of the same field giants in their calibrations, the abundances of PCA and FJ agree well over the range in [Fe/H] except for a small zero-point shift. After adjusting the abundances for a common $E(B-V)$ and a shift of +0.05 in [Fe/H] to place them on the same system as PCA, one derives the residuals in [Fe/H] in the sense (FJ – TAT), plotted in Fig. 2 as crosses. Within the uncertainties, the residuals follow the trend consistent with the transformation defined by the data of PCA; the mean [Fe/H] estimate for each cluster of FJ has been adjusted in this manner. For clusters common to the two samples, the transformation based upon the cluster mean has been applied individually to each giant in FJ, and the results for the spectroscopic and photometric approaches merged to define the mean and the standard deviation used in the final analysis for the cluster.

It should be emphasized that the inclusion of the spectroscopic sample removes one potential source of bias from the analysis. Because of the insensitivity of DDO below [Fe/H] = –0.5, it is possible that an apparent metallicity cutoff could occur in a purely DDO-based sample, shifting the mean of the abundance distribution and artificially decreasing the dispersion. For every cluster except one with [Fe/H] below –0.3, the abundance is based upon either the spectroscopic data or the combined DDO and spectroscopic abundances. As discussed above and illustrated in Fig. 2, the offset between the DDO and the spectroscopic scales at lower metallicity is constant and well-determined; it exhibits no evidence for changing sensitivity over the range of interest. NGC 2204 at [Fe/H] = –0.34, well above the sensitivity cutoff, is the only metal-poor cluster with a metallicity from DDO data alone.

2.3. The Cluster Parameters

The abundance results for the clusters are summarized in Table 1. Columns 1 through 3 give the cluster identification and its galactic coordinates. Columns 4 and 5 list the adopted reddening $E(B-V)$ as defined by the stars at the cluster turnoff and by the red giants, respectively. Column 6 explains the source of the metallicity estimate: DDO means [Fe/H] from the red giants based upon the calibration of Twarog & Anthony-Twarog (1996); DDT means the abundance of PCA adjusted for reddening and transformed using the relations discussed above; and SPE implies the spectroscopic abundances of FJ, adjusted for reddening, shifted by +0.05 in [Fe/H], and transformed using the relations cited above. For the 14 clusters that have both DDO and SPE abundances, an additional line is included and tagged with DSP. For this line, the abundance listed is the average abundance using the DDO sample and the SPE sample together. In the discussions which follow, this is the source of the [Fe/H] adopted for these clusters. The [Fe/H] is presented in column 7, followed by the standard deviation of the sample, the number of stars included in the average, and the standard error of the mean for [Fe/H]. For clusters with only two giants, the standard deviation and the standard error of the mean have been set to one-half the difference in [Fe/H] between the stars. For clusters with only one giant, the errors quoted are the average standard deviation in [Fe/H] for a single star based upon clusters with DDO abundances from 3 or more giants.

In Table 2 one can find the information relating to the galactic properties of the cluster system. Columns 1, 2, and 3 give the identification, the mean [Fe/H], and the standard error of the mean from Table 1, respectively. Column 4 identifies the means of estimating the distance modulus: MSF is main sequence fitting with the reddening based primarily upon the turnoff stars; RGC is the assumed red giant clump with the reddening based primarily upon the giants; and OTH is whatever additional method is available. For details, the reader is referred to the Appendix. Column 5 lists the apparent modulus, followed in columns 6 and 7 by the adopted apparent magnitude of the clump, if it can be identified, and M_V for the clump, derived if MSF is listed but assumed if RGC is present. Columns 8, 9, and 10 list the distances in kpc from the sun, the galactic center, and the galactic plane, respectively, on a scale where R_{GC} for the sun is 8.5 kpc.

3. The Cluster Abundance Pattern with Position

3.1. The Galactocentric Abundance Gradient

The data in Table 2 are plotted in Fig. 3a with error bars and in Fig. 3b without error bars for clarity. In Fig. 3b open circles represent rederived abundances from DDO data of indivdual stars, squares are DDO cluster abundances transformed directly from the system of PCA to the revised scale, open triangles are clusters with abundances from spectroscopic data, and filled triangles are abundances from combined spectroscopic and photometric methods. The two points joined by a line are the limiting values for BE 21 as discussed in the Appendix. Errors in [Fe/H] are the standard errors of the mean. The error bars in R_{GC} have been derived assuming that the uncertainty in the apparent modulus is the same for all clusters, ± 0.2 mag. Though on a relative scale this is probably an overestimate for clusters whose distances are based upon either main sequence fitting or the M_V of the red giant clump, it is likely to be an underestimate for the remaining clusters. Again, for specific clusters the reader is referred to the Appendix. The uncertainty in R_{GC} is derived by determining the galactocentric distance over the range in $(m - M)$. Clearly, the closer the cluster is to the sun, the smaller the absolute error in the galactocentric distance. Moreover, the error in R_{GC} is minimized for clusters with galactic longitude near 90° and 270°. Thus, the errors increase with increasing distance from the sun for clusters in the direction of the galactic center and anticenter.

It is clear from Fig. 3 that a significant change in metallicity does occur over the galactocentric range from 6.5 kpc to 15 kpc. What is not clear is the validity of the assumption that the change is linear. Not only do the clusters below [Fe/H] = –0.2 lie preferentially in the galactic anticenter, they are located exclusively beyond R_{GC} = 10 kpc, while not a single cluster with [Fe/H] > –0.15 occupies the same region. Rather than a linear transition with distance, it appears that the galactic disk contains a relatively abrupt discontinuity near 10 kpc.

To begin the evaluation of the significance of this feature, we first attempt the traditional approach of simply fitting a line through the data. We have derived the least-squares fit under three circumstances: exclusion of BE 21, inclusion of BE 21 with the low [Fe/H], and inclusion of BE 21 with the high [Fe/H]. The results are summarized in Table 3.

In the first three cases, the slope of the abundance gradient ranges from –0.077 kpc^{-1}, if the low [Fe/H] data for BE 21 are used, to –0.067 kpc^{-1} if BE 21 is excluded completely. In all three cases, the uncertainty in the slope is ± 0.008, smaller than any previous cluster study of the abundance gradient. Moreover, the probability that a correlation coefficient near 0.75 can arise from a truly random sample of this size (P_R) is well below one part in ten thousand.

What happens if we artificially break the sample into two groups based upon their location within (62 clusters) or beyond (14 clusters) $R_{GC} = 10$ kpc? For the inner group, a small gradient persists, but its statistical significance is marginal; the correlation coefficient is reduced to 0.22, which has a 9% probability of coming from a purely random sample. If we weight the data using the inverse of the standard error of the mean in [Fe/H] to enhance the impact of the clusters with more reliable abundances, the gradient weakens in size and statistical significance; there is a 19% probability that the derived gradient of –0.023 kpc^{-1} comes from a random sample. For the outer group, the small sample size is a severe limitation, though the range in R_{GC} is greater than that for the inner group. Of the three possible cases, only the one including BE 21 with the low [Fe/H] parameters comes close to producing a significant gradient and even this value is marginal. We point out that while we have excluded the unpublished spectroscopic abundances of Friel (1995) because they are preliminary in nature and lack fundamental details such as reddening estimates and error bars, the starred symbols in Fig. 7 of Friel (1995) are in excellent agreement with the above interpretation and would only enhance the result if included. Only the most distant cluster, BE 20, falls just outside the metallicity range defined by the clusters between 10 and 13 kpc.

Our interpretation of these results is simple. The dramatic change that occurs in the statistical significance of the gradient when one shifts from the complete sample to two subgroups divided purely on the basis of galactocentric position implies that rather than a continuous decline in [Fe/H] between $R_{GC} = 6.5$ kpc and 15 kpc, there are actually two distinct groups of clusters. Within each group, the metallicity gradient is weak to nonexistent. The primary difference between the two groups is in their mean metallicity; the outer clusters are, on average, 0.3 dex more metal-poor than the inner clusters. Thus, the only characteristic of significance in determining group membership for a cluster is galactocentric position.

Unfortunately, one could argue that the sample breakpoint used in the analysis is hardly objective; it was chosen specifically because Fig. 3 indicated that the gradients on either side of the breakpoint were weak. To approach the analysis somewhat more objectively, we have employed the KMM mixture-model algorithm (McLachlan & Basford 1988; Ashman *et al.* 1994) which can explore the presence and significance of multiple peaks within the cluster metallicity distribution. It should be noted that the sample is neither random nor complete; all clusters of all ages have not been included at all galactocentric distances. There are clearly fewer clusters at large galactocentric distances and the majority of these are older than 1 Gyr, in contrast with the inner clusters which include a large fraction of younger objects. However, while the sample is not ideal, it is not biased on the basis of metallicity, i.e., the clusters that were selected for photometric and/or spectroscopic

analysis were not chosen because they had peculiar or extreme abundances. If they are representative of the clusters at their galactocentric distance, then any structure found within the metallicity distribution must be tied to correlated structure in the galactocentric distribution.

The KMM algorithm objectively partitions a dataset into statistically-preferred groups and quantifies the improvement in the fit relative to a single group. These groups are fit by Gaussians either with the same variance (homoscedastic case) or unequal variance (heteroscedastic case). The algorithm returns a probability, P_{KMM}, which is a measure of the improvement of a multi-group fit to the data over a single Gaussian. P_{KMM} values below 0.05 represent significant rejections of a single Gaussian, while values in the 0.05 to 0.10 range indicate marginal rejection of the single Gaussian hypothesis. Full details are provided by Ashman *et al.* (1994).

In the present case, we have used the algorithm to determine whether two Gaussians provide a better fit to the cluster metallicity distribution than a single Gaussian. Table 4 gives a summary of the probabilities, means, dispersions, and the numbers of clusters in each group for the four options attempted: homoscedastic and heteroscedastic, low-[Fe/H] BE 21, high-[Fe/H] BE 21. The derived P_{KMM} indicate that in all cases a single Gaussian fit can be rejected; significant improvement always occurs with the adoption of two groups. For the low-[Fe/H], homoscedastic case, the cluster sample divides into two groups with only 8 clusters in the low-metallicity camp, just over half the outer clusters. The small number of metal-poor clusters is a product of the low [Fe/H] for BE 21 and the constraint that the two groups have identical variances. In the less restrictive heteroscedastic case, two groups are again found, but now 19 clusters populate the metal-poor sample, ranging from [Fe/H] = –0.15 to –0.83. The breakdown of the sample supports the discontinuity discussed previously. None of the outer clusters is assigned to the high-metallicity camp. The five clusters with $R_{GC} < 10$ kpc assigned to the low metallicity group have [Fe/H] in the range from –0.15 to –0.18 and represent the five most metal-rich clusters in the low metallicity bin.

If one adopts the high-[Fe/H] value for BE 21, the partition of the sample into two groups remains almost unchanged for the heteroscedastic case. The variance of the low metallicity group increases and an additional inner cluster with [Fe/H] = –0.13 is included. The means are essentially unaltered. For the homoscedastic case, the separation by position is even more apparent. The low metallicity bin contains 12 clusters, all beyond 10 kpc and in the [Fe/H] range from –0.54 to –0.24; only two outer clusters near [Fe/H] = –0.2 are classed in the metal-rich category. Given the uncertainty in [Fe/H] for many of the clusters under discussion, the fact that the partitions in metallicity correspond closely to

our division of the clusters about the critical location at $R_{GC} = 10$ kpc is an impressive confirmation of what we believe is apparent in Fig. 3.

To emphasize the reality of the discontinuity, we have binned the cluster sample into five groups purely on the basis of R_{GC}. As listed in Table 5, the spacing has been selected to provide similar numbers of clusters in each bin, rather than identical spacing in galactocentric distance, with the result that all the clusters beyond $R_{GC} = 10$ kpc fall within one bin. We emphasize that the spacing of the bins for clusters interior to 10 kpc is irrelevant; all that matters is the positioning of the last bin beyond 10 kpc. The abundance distribution of each bin has been analyzed with the ROSTAT package (Beers *et al.* 1990; Bird & Beers 1993) to test its consistency with a Gaussian; except for the innermost bin, all distributions are consistent with a Gaussian. The metallicity distribution of the inner bin is skew and marginally inconsistent with a Gaussian ($P = 0.070$).

For each of the metallicity distributions we have calculated the biweight estimators of location (C_{BI}) and scale (S_{BI}). These are robust estimators analagous to the familiar classical mean and dispersion of a distribution. These estimators are less sensitive to outliers than their classical counterparts—a property which can be particularly useful when dealing with samples with a small number of points (see Beers *et al.* 1990 and Bird & Beers 1993 for a full discussion). Our conclusions are unaltered if we use the classical mean and dispersion in this analysis. Also included in Table 5 are 90% confidence intervals on these parameters calculated with a bootstrap resampling technique included in the ROSTAT package.

It is apparent that inside 10 kpc, there is no evidence for a significant gradient. The mean metallicities are consistent within the errors. This changes radically for the last bin, where the mean metallicity drops by 0.30 to 0.35 dex. (Note that use of either [Fe/H] for BE 21 gives a similar result for the bin mean. This apparently contradictory result stems from the use of the biweight estimators which gives lower weight to the more extreme data for BE 21 in the low-[Fe/H] case.) What is also intriguing is the observation that the scale of the [Fe/H] distribution is effectively constant near ± 0.10 for all bins. The metallicity dispersion is important because it includes the scatter caused by the abundance determinations, by any real galactocentric abundance gradient, by any age spread, and finally by any intrinsic spread in [Fe/H] at a given position at the time of formation of the clusters.

A final consistency check that supports our interpretation of a metallicity discontinuity is provided by correcting the sample for the best-fit single linear gradient and the two weak gradients found when the clusters are divided into the two groups interior and exterior to $R_{GC} = 10$ kpc. Using the gradients listed in Table 3, we correct the metallicity of each cluster based on its galactocentric distance. Such a correction removes the contribution

to the dispersion of the metallicity distribution produced simply by either a gradient or a discontinuity. Further, one expects that the better description of the data will lead to a lower dispersion of the resulting corrected metallicity distribution.

The uncorrected scale of the total cluster sample is S_{BI} = 0.156 (0.128, 0.186) dex, where values in brackets represent the 90% confidence limits on this quantity. (We have used the high [Fe/H] value for BE 21: using the low value leads to similar results, as does the use of the classical dispersion rather than S_{BI}.) The scale of the distribution when corrected for a single linear gradient is 0.113 (0.100,0.126), whereas the scale after a correction based on the two discontinuous weak gradients is 0.097 (0.087,0.108). While the 90% confidence limits on these two values overlap, this is suggestive that a discontinuity in metallicity with galactocentric distance is a better interpretation of the cluster data. If this is the case, we predict that an expanded cluster sample will definitively show a lower dispersion for the metallicity distribution corrected for this discontinuity than a correction for a single linear trend. The metallicity spread among the clusters in the solar neighborhood will be the focus of Sec. 4.

In light of the sharp contrast between the commonly accepted view of a linear abundance gradient and that of a discontinuous disk, one might ask why this feature has remained hidden for so long. The straightforward answer is that the feature has been noted in the past (e.g., Janes 1979; Panagia & Tosi 1981; FJ; Friel 1995). However, the previous samples were inadequate to guarantee the reality of structure at this level or the feature was interpreted as a steepening of the gradient with distance, rather than a discontinuity. A recent example of this effect is seen in the work by Mollá *et al.* (1997) using a composite sample of clusters from Panagia & Tosi (1981), Cameron (1985), and Friel (1995). The overall gradients at different ages for the open clusters range from –0.089 ± 0.025 for young objects, to –0.072 ± 0.020 for intermediate age, to –0.115 ±0.037 for old clusters. What is intriguing is the result for the intermediate age group when divided into two samples at R_{GC} = 9 kpc. The inner clusters have a gradient consistent with zero, while the outer clusters show a gradient of –0.083±0.027. The presence of the outer gradient reflects the inclusion of clusters between 9 and 10 kpc in the analysis of the outer sample. The cluster sample in Tables 1 and 2 supercedes all past analyses in terms of the number of clusters, the range in galactocentric distance, and the internal consistency of the metallicity and distance scales. With significant scatter among the data points, it is plausible that a step function could be smeared into a linear gradient; the reverse process seems highly implausible.

Is it possible that the discontinuity is a product of the recalibration of the DDO metallicity scale or of the cluster selection? Though the revised DDO scale has compressed the range, primarily at the metal-rich end, it has not changed the metallicity ranking of the

clusters. As noted earlier, the possibility of a bias due to the decline in DDO sensitivity at lower [Fe/H] is removed through the inclusion of the spectroscopic data. Direct use of the PCA or FJ scale will not remove the discontinuity. The outer disk clusters would all be systematically lower in [Fe/H] by about 0.1 dex; the scatter among the inner clusters will broaden while the mean [Fe/H] shifts down by about 0.05 dex. The discontinuity is actually enhanced.

As for cluster selection, there is one source of concern. The cluster data of FJ, which dominates the analysis in the anticenter, is predominantly composed of clusters older than 1 Gyr. The sample inside $R_{GC} = 10$ kpc is heavily weighted toward younger open clusters. If there is a significant AMR among clusters, the discontinuity might be a reflection of the relative contributions of young and old clusters in different galactocentric regions. Though the sample is not as large as one might wish, if the clusters with ages beyond 1 Gyr alone are analyzed, this concern evaporates. There is little evidence for a cluster AMR among either the inner clusters or the outer clusters alone; the range in age covered by the two groups is the same, though the outer cluster sample is larger. Strangely enough, the oldest clusters in the two groups (NGC 6791 and BE 39) are also among the most metal-rich in each group.

The age distribution might play some role in the apparent increase in the mean [Fe/H] for the innermost bin in Table 5. van den Bergh & McClure (1980) and Janes & Phelps (1994) have pointed out the sharp drop in the number of older clusters interior to $R_{GC} = 7.5$ kpc. Though a large increase in [Fe/H] with decreasing age is excluded by the observations, a change of 0.05 to 0.10 dex over the last 5 Gyrs (Twarog 1980b; Meusinger *et al.* 1991) is well within the errors. If the clusters in the innermost bin are exclusively less than 1 Gyr in age, the mean [Fe/H] should be higher, independent of any radial abundance gradient.

Aside from clusters, is there any evidence to support the notion of an abundance discontinuity in the galactic disk? For reasons which will be discussed more fully in Sec. 4, we exclude the studies based upon field stars unless the stars are recently formed. Unlike clusters, field stars have the ability to diffuse over large distances on Gyr timescales (Wielen 1977), distorting if not destroying potential fine structure in the disk. Young stars, however, have not had enough time to move significant distances from their place of origin and should provide a reliable indicator of the current disk gradient. The best way to guarantee a sample of truly young stars is to pick those of high mass, though this can lead to difficulty in estimating metallicity and in comparing it with values derived from different techniques for cooler giants or lower mass dwarfs. Two stellar samples in the recent literature are of particular relevance, the spectroscopic analyses of Cepheids by Fry & Carney (1997) and of B stars in young clusters and associations by Smartt & Rolleston (1997).

Fry & Carney (1997) obtained high dispersion spectroscopy of 23 Cepheids over R_{GC} = 6 to 10 kpc; 18 of the stars were observed at more than one pulsational phase to test for any [Fe/H] dependence on the temperature scale and dwarfs were observed in two clusters to test for non-LTE effects. The mean metallicity of the sample is [Fe/H] = –0.05, which probably implies a small zero-point shift relative to our scale. What is more important is that over this galactocentric distance range, if one Cepheid at R_{GC} = 7.5 kpc with an anomalously low [Fe/H] is excluded, the derived abundance gradient is –0.003 ± 0.018 with a correlation coefficient of only 0.04. Though Fry & Carney (1997) justifiably caution against accepting this result as statistically significant given the modest galactocentric distance range, the lack of a measurable gradient, as well as the modest dispersion in [Fe/H] at a given R_{GC}, are clearly consistent with the cluster data over the same region.

Smartt & Rolleston (1997) have compiled and analyzed in a homogeneous manner spectra of 21 B stars in open clusters and the field. Their metallicity indicator is [O/H], not [Fe/H], so some concern exists over the relevance to the current discussion. Since the nucleosynthetic origins of O and Fe are different, it is possible for a galactic gradient to occur in one element and not the other. The focus of the B star analysis is the apparent discrepancy between gradients identified through [O/H] measures in nebular regions (HII and planetary nebulae) and B stars. Abundance gradients of d[O/H]/dR = –0.06 ± 0.02 kpc^{-1} are found in all the nebular studies, while B stars exhibit little or no gradient. Since B stars should be representative of the current interstellar medium, this presents a problem. Smartt & Rolleston (1997) attribute the lack of a gradient in previous studies to small samples, and errors in distances and abundances; they derive a gradient of –0.07 ±0.01 kpc^{-1}. Closer examination of Fig. 1b of Smartt & Rolleston (1997) shows that an alternate interpretation is well within the errors of the data. The 11 B stars between R_{GC} = 6 and 10 kpc, the majority of which have small uncertainties in both distance and abundance, exhibit no gradient at all. The mean [O/H] is –0.06 with a dispersion of only 0.09 dex, fortuitously similar to the Cepheid result. Again, we caution about overinterpreting the absolute abundances given the possibility of scale shifts, but the modest dispersion is real. Given that the errors in the [O/H] determinations are comparable to the dispersion, this implies that all the B stars have the same abundance, within the uncertainties. The entire source of the gradient comes from the 10 points beyond 10 kpc, the majority of which have significantly larger errors in both distance and abundance. There is no question that, in the mean, [O/H] of the outer disk stars is lower by about 0.4 dex; whether this is due to a gradual change in [O/H] with distance or a discontinuity remains determined by the eye of the beholder. In contrast, the lack of a gradient between R_{GC} = 6 and 10 kpc from these very young stars is in direct contradiction with the results of Luck (1982), who finds d[Fe/H]/dR = –0.13 ±0.03 kpc^{-1} from 50 late type supergiants over R_{GC} = 7.7 to 10.2 kpc.

An equally tantalizing picture is painted by the nebular results. Most recent work (e.g., Fich & Silkey 1991; Maciel & Koppen 1994; Simpson *et al.* 1995) indicates a variation in the abundances of a number of elements across the galactic disk, confirming the earlier work by Shaver *et al.* (1983). However, the number of points, the analytical approach, and the range of galactocentric distance varies significantly from study to study, and none of the studies measure Fe. Thus, one is faced with many of the same problems that plagued past attempts at deriving fine structure within the disk using stars and clusters. It is intriguing to find, however, that despite the problems, possible evidence for fine structure is not absent from the nebular surveys. Simpson *et al.* (1995) claim that their abundance data, ranging from $R_{GC} = 0$ to 10.5 kpc, can be described by a linear gradient with the mean abundance decreasing with distance or equally well by two zones without gradients but linked via a discontinuity in the abundances at 6 kpc, i.e., there is no abundance gradient between 6 and 10 kpc from the galactic center. Though their data end where our discontinuity begins, they point to the work of Fich & Silkey (1991), Dinerstein *et al.* (1993), and still unpublished results to suggest that a second discontinuity does exist beyond 10 kpc.

The conclusion that a step function fits the data interior to 10 kpc as well as a linear relation has been challenged by Afflerbach *et al.* (1997) using 34 compact HII regions between 0 and 12 kpc. They find linear gradients of approximately –0.07 kpc^{-1} for [N/H], [S/H], and [O/H], uncertainties in the slopes comparable to our linear fits for the entire cluster sample, and correlation coefficients near 0.7. They exclude a step function because analysis of only HII regions beyond 6 kpc does not eliminate the gradients, though they are reduced. However, of the 18 regions beyond 6 kpc, 4 lie beyond the discontinuity at $R_{GC} = 10$ kpc. The key question is not if the data can be fit by a linear relation; they can be. What matters is whether or not one can, given the sample size and the error bars, distinguish between a step function and a linear relation. The nebular data to date are, at best, inconclusive. Additional concern comes from the absolute abundances derived from the nebular samples, a point we will return to in Sec. 4.

3.2. The Abundance Gradient Perpendicular to the Plane

A prime motivation for this investigation was the claim by PCA that a gradient in [Fe/H] existed among clusters perpendicular to the plane, contradicting earlier cluster analyses but consistent with field star studies (e.g., Yoss *et al.* 1987; Sandage & Fouts 1987; Yoshii *et al.* 1989; Ratnatunga & Freeman 1989; Morrison *et al.* 1990). With the recognition that the cluster distribution is approximately a step function rather than a linear gradient, it is straightforward to show that the gradient perpendicular to the plane

is an artifact of the PCA analysis. In Fig. 4, the absolute Z distance is plotted for all the clusters in Table 3 as a function of [Fe/H]; open circles are clusters included in PCA while crosses are clusters added to the current sample primarily through the data of FJ. No correction has been applied for the galactocentric trend and a Z-gradient is obvious. PCA next applied a linear correction to the sample to eliminate the radial trend and found that a residual gradient still remained away from the plane. The source of the problem is seen in Fig. 5, where the absolute Z position is presented as a function of R_{GC}. Though there are some older clusters within $R_{GC} = 10$ kpc which are located well away from the plane, the majority of the clusters are younger and lie within 200 pc of the disk. In contrast, the clusters beyond 10 kpc are predominantly older and are positioned well away from the plane. Thus, the discontinuity in [Fe/H] is paired with a discontinuity in Z distribution. For purposes of resolving the question at hand, it makes no difference whether this change is real or simply a selection effect in the cluster sample. Note also that the cluster sample of PCA exends just beyond the discontinuity. If, instead of correcting for a linear gradient, one merely applies a zero-point offset of 0.32 dex to the outer clusters, one gets the revised version of Fig. 4 as presented in Fig. 6; the Z-gradient disappears.

4. The Metallicity Distribution in the Solar Neighborhood

4.1. Galactic Clusters and Field Stars: The Discrepancy

Questions of the galactocentric gradient aside, the cluster sample allows one to place another constraint on the chemical history of the galactic disk. Assuming that the clusters are not affected by a significant AMR, that clusters are not atypical of the interstellar medium in the disk at the time of their formation, and that the intrinsic metallicity spread within the interstellar medium does not change significantly over the lifetime of the disk, one can use the metallicity distribution among the clusters to sample the degree of inhomogeneity among the stars forming at a random time within the disk. For our sample, we will only use clusters between $R_{GC} = 6$ and 10 kpc. A small correction to each [Fe/H] based upon galactocentric position and the derived small abundance gradient among the inner clusters (see Table 3, unweighted) has been applied. For our purposes it is irrelevant whether this gradient exists because of an intrinsic gradient with position at a given age, because of an AMR convolved with a change in the mean age of the sample with galactocentric distance, or both. Our only interest is in the dispersion in [Fe/H] at a given location at a given time. From 62 clusters, the corrected data have a mean [Fe/H] of $+0.010$ and a robust dispersion of only ± 0.096 (0.085, 0.108). The distribution is slightly boxier than a Gaussian. Because this dispersion includes any residual trends with age or

galactocentric position and the observational uncertainties in the abundance estimates, it should be regarded as an upper limit to the intrinsic metallicity dispersion within the interstellar medium.

This dispersion seems small compared to past discussions of the cluster distribution (e.g., Carraro & Chiosi 1994; Friel 1995), but it should be remembered that we have excluded the clusters beyond 10 kpc, the abundance correction due to the gradient is based solely upon the inner clusters and therefore actually narrows the dispersion, and the change in the metallicity scale for the giants has compressed the previous scale for the inner clusters. That is not to say that a true range in [Fe/H] does not exist among clusters formed at approximately the same time; it does. This result merely corroborates the earlier investigations of smaller samples with precise abundances by Nissen (1988) and Boesgaard (1989). Nissen (1988) used $uvby\mathrm{H}\beta$ photometry of F-dwarfs in 13 nearby open clusters with ages between 0 and 2 Gyr to study the metallicity spread. The mean [Fe/H] = +0.05 with a dispersion among the clusters of only $\pm$ 0.08; no correlation was found between [Fe/H] and age. For reference, 9 of the clusters in Nissen (1988) are found in the current investigation; the mean difference in [Fe/H] in the sense (NI – Table 2) is 0.00 $\pm$ 0.10.

Boesgaard (1989) used high dispersion spectroscopic analysis of F dwarfs in 6 galactic clusters, all younger than 1 Gyr, to study the metallicity spread in the solar neighborhood. Though the sample is small, the abundance estimates have unusually high precision for open clusters. Boesgaard (1989) finds a mean [Fe/H] of +0.015 and a dispersion of only 0.087. These two studies are consistent with what is found above: the [Fe/H] range among open clusters in the solar neighborhood is between 0.3 an 0.4 dex wide, from [Fe/H] = –0.2 to +0.2, with no evidence that this has changed significantly over the last 5 Gyr, and a mean near solar. (A note of clarification: the parameter used to describe the inhomogeneity in [Fe/H] among stars and clusters in the solar neighborhood varies from study to study. The distribution of clusters inside 10 kpc is robust fit to a Gaussian though the distribution is not a perfect match to a Gaussian. The dispersions quoted for the smaller studies do not assume a Gaussian profile and represent the traditional standard deviation about the mean. Our conclusions are unchanged if we use the more classical measure of the dispersion. The range in [Fe/H] is more appropriate when a Gaussian distribution is a poor representation, e.g., when the sample of all the clusters is best represented by the sum of two Gaussians. As observed above, the range is about two to three times larger than the dispersion, a fact which should be kept in mind when comparing the results from different investigators.)

How does this compare with the results from field stars within the solar neighborhood? In Sec. 3, we discussed the results for young stars as defined by the Cepheids and the B stars inside 10 kpc. In both instances, the dispersion in metallicity from either O or Fe is typically

±0.10 dex or less with a mean abundance near solar, in excellent agreement with the cluster data. Venn (1995) derives a mean of solar abundance for 13 metals from spectroscopic analysis of 22 A supergiants, though the abundance dispersion is closer to ±0.2 due to the larger uncertainties in the individual abundances. Before discussing an expanded sample of field stars near the sun, an issue raised in Sec. 3 should be dealt with. The metallicity distribution of the young clusters and the young stars definitively demonstrates that the mean metallicity among recently formed objects is solar within ±0.1 dex. The cluster sample indicates that at the R_{GC} of the sun, this mean metallicity is basically the same as when the sun formed 4.6 Gyr ago. Despite the extraordinary agreement, analyses of galactic nebular abundances (e.g., Afflerbach *et al.* 1997) consistently find that the ISM near the sun is metal-deficient by about [m/H] = –0.3. It has become commonplace to explain this discrepancy as evidence that the sun is anomalously metal-rich for its age and location. The data for the young stars and the young open clusters demonstrate that if the sun is anomalously metal-rich, so is the typical star formed at R_{GC} = 8.5 kpc over the last 1 Gyr. We suggest that the source of the discrepancy lies with the nebular abundances, i.e., they systematically underestimate the metal content of the HII regions by about 0.3 dex in the solar neighborhood. Potential problems with nebular abundances have been under discussion for some time, as evidenced by the work of Mathis (1995) and Alexander & Balick (1997). However, whether the origin of the proposed deviation is found within the clouds, within the models, or both is beyond the scope of this investigation and the expertise of the investigators.

Returning to the field star metallicity distribution, the picture relative to the young stars and the clusters changes dramatically when one expands the sample to include any and all field stars near the sun. The most comprehensive analysis of the local metallicity distribution to date is that of Wyse & Gilmore (1995; hereafter referred to as WG). In Fig. 7 we compare the normalized abundance distribution of the clusters (solid curve) to the Thin Disk (dash-dot curve) and Thin + Thick Disk (dashed curve) samples of WG. The [Fe/H] scales of the latter two histograms have been offset to make the curves more distinguishable. It is apparent that, zero-point uncertainties aside, the field star population in both groups contains an excess of stars below [Fe/H] = –0.2 which is not reflected in the cluster sample. The only subset of WG which comes close to reproducing the cluster distribution is that listed by WG as Young Disk.

The disagreement between the field stars and the clusters implies that they do not sample the same distribution of galactic populations. This difference is an important clue to the chemical history of the disk and suggests a straightforward solution. The similarity of the cluster population to the Young Disk but not the Thin Disk implies that the discrepancy arises from differences in the age distributions of clusters and field stars. The

cluster sample contains a significant fraction of clusters with ages less than 1 Gyr, a rapidly declining sample with increasing age, and no clusters older than 9 Gyr; the long-lived field stars provide a more representative distribution of the entire disk lifetime. The discrepancy will arise if field stars with [Fe/H] $<$ –0.2 are predominantly members of the old disk, i.e., they fall in the age range of 8 to 13 Gyr and do not overlap in age with the surviving cluster population. There was an open cluster population which overlapped with this field star group but it has been tidally disrupted.

Such an explanation is consistent with a significant increase in [Fe/H] within the interstellar medium during the first third of the lifetime of the galactic disk, followed by a much more gradual increase over the last 8 Gyr. This trend is in qualitative agreement with the analyses of field stars in the solar neighborhood as discussed by Twarog (1980b) and revised by Meusinger *et al.* (1991). (The revision by Carlberg *et al.* (1985) is invariably cited in discussions of the AMR to illustrate the changes in the relation as the analysis and the isochrones are altered and/or improved. Because of biases in the data selection and analysis, including those discussed by Nissen (1995), the AMR derived by Carlberg *et al.* (1985) is unreliable for old disk stars and should not be included in the discussion.)

In contrast, though the qualitative AMR trends found by Edvardsson *et al.* (1993; hereafter E93) and Jønch-Sørensen (1995) generally agree with the earlier work, the mean metallicities at a given age are systematically lower than derived in the earlier work and the ranges in [Fe/H] are large enough that stars with [Fe/H] well below –0.2 can be found at any age beyond 2 Gyr. In fact, the mean [Fe/H] at the age of the sun is between –0.15 and –0.20 for E93, similar to the value found by Jønch-Sørensen (1995) for stars near the solar circle. The mean for the entire sample at the age of the sun for Jønch-Sørensen (1995), a sample which is dominated by stars interior to R_{GC} = 10 kpc, is closer to [Fe/H] = –0.35. More important, the range in [Fe/H] among field stars 4 Gyr old and older for both studies is between 0.6 and 0.8 dex. Due to the [Fe/H] selection bias, for E93 the dispersion is of questionable value; the range is a more reliable indicator. Twarog (1980b) finds [Fe/H] = –0.05 at 4.6 Gyr and a dispersion in [Fe/H] near 0.1 dex for for stars younger than the sun. If the stellar samples in E93 and Jønch-Sørensen (1995) are representative of the ISM in the solar neighborhood over the last 10 Gyr, a difference in the age distribution cannot explain the discrepancy with the clusters. Clusters with [Fe/H] = –0.2 or lower should be typical of the sample for ages greater than 2 Gyr and the mean metallicity for clusters greater than 1 Gyr in age should be well below solar. (The mean AMR for the solar neighborhood as defined by E93 is included in the discussion because it has become a standard reference on the relation despite the [Fe/H] bias in constructing the sample. The mean abundances with age cannot be considered reliable (Nissen 1995)).

If one accepts that the surviving clusters are not atypical of the ISM in the solar neighborhood, even in the 4 to 8 Gyr range, the resolution of the discrepancy must reside with the field stars. Before discussing the probable solution, an often-cited but incorrect option should be eliminated. In AMR studies F dwarfs are commonly chosen because they evolve on timescales typical of the lifetime of the galactic disk, a few Gyr. However, while young stars of any mass that fall within the F-star temperature range are observable, as a sample ages, the hotter F dwarfs evolve out of the temperature range and are eliminated. Thus, only the lowest mass F dwarfs will survive over the entire lifetime of the disk. Because the metallicity and mass of a main sequence star determine the star's temperature, the probability of finding a star of a given [Fe/H] in a temperature-limited sample changes with age. In general, the limiting age at which one may still observe a star of a given [Fe/H] declines as [Fe/H] increases. Friel (1995) cites this selection bias (McClure & Tinsley 1976; Knude 1990) as the explanation for the existence of an AMR among the field stars while none occurs within the cluster sample.

However, the selection biases outlined by McClure & Tinsley (1976) were well known and were minimized in the sample selection procedure of Twarog (1980a) and the analysis of the sample by Twarog (1980b). All of the effects detailed by Knude (1990) were modelled and incorporated in the analysis of the F dwarfs by Twarog (1979), as summarized in Twarog (1980a,b). While it is impossible to completely eliminate [Fe/H]-dependent bias in an F-star sample, the models and analysis in Twarog (1980a) show that for the observed sample, the AMR is not simply a reflection of selection bias. This conclusion is confirmed by the discussion of WG who use only long-lived G dwarfs in their sample, thereby avoiding the possibility of excluding metal-rich, older stars. The G dwarfs also produce a metallicity distribution heavily weighted toward metallicities lower than the average inner cluster.

4.2. Galactic Clusters and Field Stars: A Solution

The fundamental discrepancy is that the metallicity distribution of the surviving open clusters in the solar neighborhood at all ages is missing the lower metallicity portion of the field star distribution. The work of E93 and Jønch-Sørensen (1995) implies that the metal-weak thin disk can be as young as 2 to 4 Gyr. Where do the lower metallicity field stars come from if they don't come from the local disk? The answer is supplied by looking at the cluster sample. While there are no clusters interior to 10 kpc which overlap with the metal-poor field stars, there is a rich population of clusters beyond this location which bracket the required [Fe/H] and age ranges. The large spread in [Fe/H] within the cumulative cluster sample is often cited as confirmation of the large range in

metallicity derived among the field stars as in E93. But the existence of a discontinuity (or steep gradient) in the disk guarantees that the metal-poor clusters beyond R_{GC} have no bearing on the discussion of the ISM near the sun and cannot be combined with the local distribution. The property which makes the clusters different from the field stars isn't the age but the mass. Though clusters can have galactic orbits which are non-circular, causing them to move over a range in galactocentric distance as they go around the galaxy (see, e.g., PCA), their collective mass ensures that orbital perturbations caused by the passage of stars and/or massive gas clouds will be negligible. In contrast individual stars can experience considerable orbital perturbations from the cumulative effects of such interactions. Thus, when combined with the spatial analysis of Sec. 3, it is concluded that a significant fraction of the stars in the solar neighborhood with [Fe/H] < -0.2 are interlopers. These stars are the field star counterparts to the metal-poor cluster population beyond $R_{GC} = 10$ kpc. The stars have diffused inward on timescales of a few Gyr, mixing with the local population to a degree which makes it impossible to distinguish them dynamically from the locally formed field stars of comparable age. The remainder of this section will focus on the plausibility of this solution and how it fits in with the the current picture of the field star population near the sun.

Before addressing the field star question, a puzzling point regarding the cluster population should be dealt with. Though one can readily assume that significant alteration in the galactocentric orbits of the clusters is unlikely, how much diffusion in galactocentric distance arises because of the spread in initial conditions among the clusters? If one takes the orbital analysis by Carraro & Chiosi (1994) and PCA at face value, clusters near the sun typically range over about 3 kpc in galactocentric distance as they orbit. Under such conditions, survival of a sharp discontinuity in the galactic abundance gradient as defined by the clusters seems improbable.

Our clearly biased interpretation of this contradiction is that the problem lies with the orbits. Neither Carraro & Chiosi (1994) nor PCA give any indication of the uncertainties in their orbital parameters due to potential errors in distance, radial-velocity, proper motion, or assumed galactic potential. An indication of the difficulties in interpreting these kinematic results is available by comparing the orbits for the five clusters in Carraro & Chiosi (1994) with the same objects in the larger sample of PCA. The ranges in galactocentric distance for clusters in PCA were all significantly larger than found by Carraro & Chiosi (1994); the *increase* in ΔR_{GC} went from a low of 0.9 kpc for NGC 2420 to 4.8 kpc for NGC 2506. Even more significant is the distribution in orbital eccentricity, e, defined as the difference between apogalacticon and perigalacticon divided by their sum. Of the 19 clusters in PCA, only one has e below 0.1. If one excludes the extreme case of NGC 7789 ($e = 0.6$), the remaining 18 clusters have a mean eccentricity of 0.19, implying an average range near 4

kpc in galactocentric distance for a cluster at R_{GC} = 10 kpc. No significant difference is found comparing clusters sorted by age. While field star samples covering a large range in age can exhibit average eccentricities at this level, they are implausible for an unbiased open cluster sample. The ineffectiveness of cluster perturbations should lead to average eccentricities only slightly larger than found among newly formed clusters and stars, i.e., closer to 0.0 than 0.2. Turning the question around, based upon the expected distribution of e and the existence of the cluster discontinuity, recent derivations of the cluster orbits have overestimated the orbital eccentricities and most clusters diffuse over a much smaller range than claimed. Even if one chooses a typical value of $e = 0.1$ for the clusters, at R_{GC} = 10 kpc, a cluster will orbit between R_{GC} = 9 kpc and 11 kpc, enough to round off the edges of the discontinuity but not enough to destroy it.

Since the work of E93, a great deal of effort has been expended to explain the origin of the large dispersion in [Fe/H] among stars of a given age near the sun; a useful summary of the many options is given in van den Hoek & de Jong (1997). Out of the many suggestions, the one of primary relevance is that of Wielen *et al.* (1995; hereinafter WFD). The goal of WFD was to determine the galactocentric origin of the sun based upon the assumption that over 4.6 Gyr it has diffused away from its initial location. This can be done if one assumes that: (a) the original dispersion in [Fe/H] within the ISM at a given age at a given galactocentric location was significantly smaller than that observed among stars more than a few Gyr old; and (b) a significant galactocentric gradient in [Fe/H] exists within the disk. If one knows the AMR, the galactocentric origin of a star of a given age can be derived by measuring how much it deviates in [Fe/H] from the mean value for its age, and moving the star along the galactocentric abundance gradient by an amount which accounts for the deviation. Following this approach, WFD derive R_{GC} = 6.6 ±0.9 kpc for the birthplace of the sun and, more important, conclude that the initial dispersion in [Fe/H] within the ISM at a given R_{GC} is rather small, i.e., the range in [Fe/H] found in E93 is a product of diffusion.

The solution we propose is qualitatively the same as WFD, but has been modified to account for the results of Sec. 3. Before we discuss those details, a general comment on the role of stellar diffusion is in order. The theoretical and observational role of stellar diffusion has been the focus of numerous investigations over the years (Mayor 1976; Grenon 1987; Francois & Matteucci 1993; Fuchs *et al.* 1996, among others). For the current discussion and that of WFD, the most important analysis is that by Wielen (1977). Its conclusions are simple but, if correct, devastating to any investigation which attempts to sort stars into bins of common origin through kinematics. As summarized in Mihalas & Binney (1981) and reiterated in WFD, the randomizing effects of diffusion on the orbits of stars, coupled with an imperfect knowledge of the galactic gravitational potential both in space and time, make

the tracing of stellar orbits of older stars back in time to locate their initial birthplaces a hopeless task. If the arguments of WFD are correct, the conclusion of E93 that diffusion is inadequate to explain the dispersion in [Fe/H] based upon the approach of Grenon (1987) is flawed. A more recent attempt to constrain the role of diffusion by van den Hoek & de Jong (1997) is equally questionable on kinematic grounds and because it depends upon the existence of well-defined radial gradients in O and Fe.

Assuming that stellar diffusion does occur and the timescales discussed by Wielen (1977) are valid, how does one explain the discrepancy between the field stars and the clusters? First, over the last 8 Gyr the mean [Fe/H] of the ISM between 6 and 10 kpc has been solar within ±0.10 dex. Beyond a possible gradual change in [Fe/H] with time, the dispersion in [Fe/H] at all ages has remained ±0.09 dex or smaller. In short, stars formed in the 6 to 10 kpc range typically have [Fe/H] between –0.2 and +0.2. Over the same galactocentric distance range, the abundance gradients in various metals have remained shallow to flat, i.e., no gradient. Thus, the sun is **not** atypical of the solar neighborhood 4.6 Gyr ago, a point emphasized in significantly more detail by E93. Because no gradient in [m/H] exists, the sun could have formed anywhere in the 6 to 10 kpc range. In general, the approach outlined by WFD to identify the birthplace of field stars becomes moot.

Second, a virtually identical description applies to the galactic disk between $R_{GC} = 10$ and 15 kpc, with minor modification. The mean [Fe/H] in the outer disk is –0.35, and the dispersion might be larger, i.e., stars in the range from –0.60 to –0.10 form there. Stars between 6 and 10 kpc diffuse toward $R_{GC} = 8.5$ kpc, but have no impact on the overall metallicity distribution; they do change the kinematic distributions with age. However, stars beyond $R_{GC} = 10$ kpc also diffuse inward, reaching the solar circle on timescales of 2 to 3 Gyr (Wielen 1977). Because the [Fe/H] distribution beyond $R_{GC} = 10$ kpc is independent of distance, it makes no difference whether a star comes from $R_{GC} = 10.5$ kpc or 14.5 kpc. Because these stars are kinematically indistinguishable from locally formed stars of similar age, they cannot be isolated from the solar sample and should increase in number with age. The net result is that the metallicity range among field stars should remain small among stars younger than 2 to 3 Gyr, but increase dramatically beyond this age and remain effectively constant up to about 8 Gyr. This effect is seen to varying degrees in Twarog (1980b), Meusinger *et al.* (1991), E93, and Jønch-Sørensen (1995). Among the oldest stars (> 8 Gyr), the exact trend is difficult to predict. If, as discussed in Sec. 5, the AMR interior to $R_{GC} = 10$ kpc drops between 9 and 12 Gyr ago, the observed dispersion depends upon a variety of poorly known factors: the ratio of inner disk to outer disk field stars in the sample, the AMR in the outer disk over the same age range, the increasing uncertainty in the age determination among older stars, and the selection bias discussed above which places a cap on the metallicity of the stars detectable in the oldest age bins.

5. A Summary and A Scenario

An extensive collection of open cluster data has been compiled, standardized, and merged to permit an analysis of the spatial and chemical properties of the disk sampled by the cluster population. It is concluded that:

a) The abundance distribution with galactocentric distance for the disk clusters is best described by a step function rather than a linear gradient. Inside $R_{GC} = 10$ kpc there is, at best, a shallow abundance gradient which may be the product of the age distribution of the sample. Beyond 10 kpc, the sample is too small to determine if a comparable gradient exists. The discontinuity at 10 kpc separates the cluster sample into two groups that differ in mean [Fe/H] by about –0.35 dex.

b) There is no evidence for a gradient in abundance perpendicular to the galactic plane for open clusters. The clusters beyond $R_{GC} = 10$ kpc included in past discussions have, on average, larger Z distances that those within 10 kpc. When coupled with a true discontinuity in [Fe/H], a linear correction with galactocentric distance leaves a residual effect which translates into a vertical gradient.

c) The metallicity distribution for the clusters is well described by two Gaussians identified with the inner and outer clusters. After correcting for a slight abundance gradient for the inner clusters, the dispersion in [Fe/H] for the open clusters at the solar circle reduces to ± 0.09 dex while the average [Fe/H] is approximately solar. Though the sample of clusters greater than 1 Gyr in age is modest, there is no indication that either the mean or the dispersion is a significant function of age. This implies that the metallicity of the sun is not atypical for its age.

d) The metallicity distribution for the inner clusters disagrees with that derived for field stars in the solar neighborhood. Though the lack of an abundance gradient removes the specific solution proposed by WFD to explain the large dispersion in [Fe/H] among the field stars, the general idea of diffusion as the primary culprit survives. The large metallicity range found among stars with ages greater than 3 Gyr is the product of diffusion of stars from beyond $R_{GC} = 10$ kpc. It should be emphasized that the small dispersion in the cluster metallicity distribution at the solar circle is independent of the nature of the galactocentric abundance gradient. The discontinuity, however, provides a means of increasing the metallicity range among the field stars in the absence of a linear gradient.

Though the empirically derived trends and the evolutionary scenario are internally consistent, one key piece of the puzzle is still missing: why does a discontinuity exist? In reality, this question can be broken down into two equally difficult problems: how is a discontinuity created, and how is it maintained over 10 to 12 Gyr? The solution

undoubtedly lies in understanding why R_{GC} = 10 kpc is so special. Given the current state of the data and the justifiable uncertainty regarding the reality of the discontinuity, a detailed explanation of the origin of the discontinuity is neither feasible nor warranted. We can, however, offer a qualitative scenario which fits the observational evidence at present, both for clusters and field stars.

The primary difference between the inner and outer clusters is a mean metallicity which differs by 0.3 to 0.4 dex. As noted earlier, there is no evidence that the mean abundance in either zone has changed significantly over the last 8 Gyr though, again, increases on the order of 0.1 dex cannot be excluded. In most models of galactic chemical evolution, as time passes the mean metallicity of the gas out of which the stars form will approach some limiting value in [m/H], in large part because of the logarithmic nature of [m/H]. The limiting value is some fraction of the nucleosynthetic yield; the exact value of the fraction depends upon the stellar yields, the initial mass function, gas flows, and the element under consideration. Thus, it is possible that the effective yield for the chemical evolution of the outer disk is simply lower than that of the inner disk for some currently unknown reason. As an alternative, we offer the following scenario:

The discontinuity at R_{GC} = 10 kpc is a reflection of the original boundary of the newly formed disk, currently referred to as the thick disk. Chemically and kinematically, the thick disk is associated with the disk globular cluster population typified by 47 Tuc and M71, and extends to, at least, the solar circle (Armandroff 1993; Zinn 1996 and references therein). Through the use of the rich population of open clusters, the exact radial boundary of the thick disk is set at R_{GC} = 10 kpc. As outlined by WG based primarily upon the data of E93, this population originated about 12 Gyr ago when the typical metallicity of the gas near R_{GC} = 10 kpc was [Fe/H] $\sim$ –1.0. It is assumed that the thick disk evolves dynamically and chemically as a separate entity from the surrounding halo in that while gas may infall from the halo to the disk, the evolution of the thick disk has little impact on the surrounding halo. While the metallicity within the thick disk rises from [Fe/H] $\sim$ –1.0 to –0.6, the mean metallicity in the surrounding halo remains relatively unchanged. Between 10 and 8 Gyr ago, the mean [m/H] of the inner disk increased rapidly from –0.6 to approximately –0.1 and the inner disk evolved from the thick disk to the standard thin disk. How quickly this occured remains unknown, but by 8 Gyr ago, the mean [m/H] was close to solar. Over the same time scale the outer disk takes shape, and chemical evolution follows a similar trend. However, the initial metallicity of the outer disk remained [m/H] $\sim$ –1.0 because of the lack of the thick disk phase that drove the chemical enrichment of the inner disk. In the long run this produced a difference in the current [m/H] of the inner and outer disks which reflects the offset between the typical thick disk star ([m/H] = –0.6 to –0.7) and the halo transition ([m/H] = –1.0).

If nothing additional occurred, one should expect the metallicity distribution near the sun to reflect three populations: thick disk with [m/H] between –1.0 and –0.5, thin disk with [m/H] between –0.3 and +0.2, and a transition population connecting the two. The size of the transition population depends upon the timescale over which it evolved and the star formation rate during this period, neither of which are known. This rather classic picture of disk formation is distorted by the additional factor of diffusion from the outer disk. Because the mean [m/H] in the outer zone has remained constant for such a long time, the metallicity distribution of the diffused stars is dominated by stars in the [m/H] range from –0.1 to –0.6, exactly the range occupied by the transition population, and merges locally to become what WG refer to as the metal-weak thin disk.

For the additional question of the survival of the discontinuity, we have no explanation. If the initial metallicities of the gas in the outer and inner disk were systematically different, one would expect radial gas diffusion to play a role in smearing, if not wiping out, the discontinuity over the timescale of a few Gyr. Yet the discontinuity has survived until at least 1 Gyr ago. The potential discontinuity at $R_{GC} = 6$ kpc proposed by Simpson *et al.* (1995) is located at the outer edge of a ring of molecular clouds and associated spiral arms; they suggest that the step function is due to radial mixing driven by the presence of a bar. This suggestion has no direct bearing on what happens at 10 kpc except to highlight the need for a dynamical boundary separating the gas in the inner and outer zones. Potential evidence for some dynamical difference between the inner and outer zones is supplied by the scale height of the clusters.

Though the sample is by no means complete and the plot includes clusters younger than 1 Gyr in the inner zone, the Z distribution of clusters in Fig. 5 suggests that the scale height of the old cluster population in the outer zone may differ from that in the inner zone. Janes & Phelps (1994) have analyzed the Z distribution of the old clusters and derived a scale height of 325 pc, significantly larger than the 55 pc estimate from young open clusters. Because the ages of the older sample range from 1 to 9 Gyr and diffusion in the Z direction will not work for clusters, one is left with tidal disruption of clusters near the galactic plane or satellite mergers to explain the apparently large scale height. The former explanation is rejected because any attempt to explain the large-Z clusters as the high-Z tail of the thin disk population overproduces the observable number of clusters near the plane, even accounting for tidal disruption. Thus, the old cluster Z-distribution implies evidence for regular mergers over the last 10 Gyr.

Given the discontinuity in the disk, an alternate interpretation comes to mind. A fundamental assumption of the Janes & Phelps (1994) analysis is that all the old clusters come from the same population. Thus, when a scale height is derived, it is applicable to

the cluster count at all galactocentric radii. If the discontinuity at 10 kpc applies to scale height as well, i.e., the larger Z range for clusters beyond 10 kpc in Fig. 5 is real, the scale height of 325 pc derived by Janes & Phelps (1994) is a composite. For the cluster sample interior to R_{GC} = 10 kpc, the true observed scale height is intermediate to 55 pc and 325 pc, the product of an original scale height near 55 pc, altered by tidal disruption over time through preferential destruction of the clusters near the plane. Beyond R_{GC} = 10 kpc, the scale height is unknown; we have no real information on the scale height of old clusters beyond 10 kpc because there is little reliable information on the number of clusters near the galactic plane. While those away from the plane are easily discovered, those within the disk remain hidden by dust or within a rich background field of stars; this is apparent if one compares the radial distribution of old and young clusters (Figs. 7 and 9) in Janes & Phelps (1994) for $R_{GC} > 10$ kpc. If the scale height of the young disk in the outer zone or, more important, of the disk at the time of formation of the older clusters is greater than 55 pc, when combined with selection effects and the lower probability of tidal disruption at larger galactocentric distance, the excess of high-Z clusters can be reduced. This still implies that the true scale height of the outer disk is greater than that of the inner disk; additionally, it is likely that cluster disruption is more efficient inside R_{GC} = 10 kpc. If either suggestion can be confirmed observationally, it would support the notion of a dynamical difference between the inner and outer galaxy. Note that the suggestion of a thicker disk in the outer galaxy is also consistent with the explanation of mergers as a thickening agent in galactic evolution (Janes & Phelps 1994).

We close this paper on a somewhat pessimistic, but debatable, note. A primary goal of field star studies is to delineate the chemical evolution of the disk at a particular location over time. All the studies of the AMR to date have been premised on the assumption that one can isolate a field star sample ranging in age over the lifetime of the disk which typifies the ISM at the solar circle over that same timescale, i.e., it has been assumed that stellar diffusion did not mix stars from significantly different galactocentric origins. If the arguments of Wielen (1977) and WFD are correct, this assumption fails and kinematics cannot be used to sort stars indivdually into bins of galactocentric origin. With the existence of a linear abundance gradient, WFD showed that the metallicity could be used to distinguish among stars formed at various galactocentric distances. If the cluster analysis above is correct, this positional tag is eliminated. The net result is that unless an alternative method is derived for isolating the metal-weak thin disk stars which come from beyond R_{GC} = 10 kpc from those which formed locally as part of the transition between the thick and the thin disk, any attempt to understand the chemical and dynamical history of the disk at the solar circle using field stars may remain an exercise in futility. One possibility is that at a given [Fe/H], the outer zone stars might exhibit abundance ratios, e.g., [O/Fe] or [Ca/Fe],

which separate them from the inner sample. Clusters represent the ideal object but any clusters formed in the thick disk have long since been destroyed and any distant clusters in this age range well beyond the solar circle tell us nothing about the local galactic disk.

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Fig. 1.— The absolute magnitude of the red giant clump as a function of (a) metallicity and (b) age. For Fig. 1b, cluster identifications are aligned vertically with the points.

Fig. 2.— Metallicity differences between the revised DDO abundances and those of PCA (open circles) and FJ (crosses), in the sense (REF - DDO). The data of FJ have been shifted by +0.05 in [Fe/H] to place them on the PCA scale.

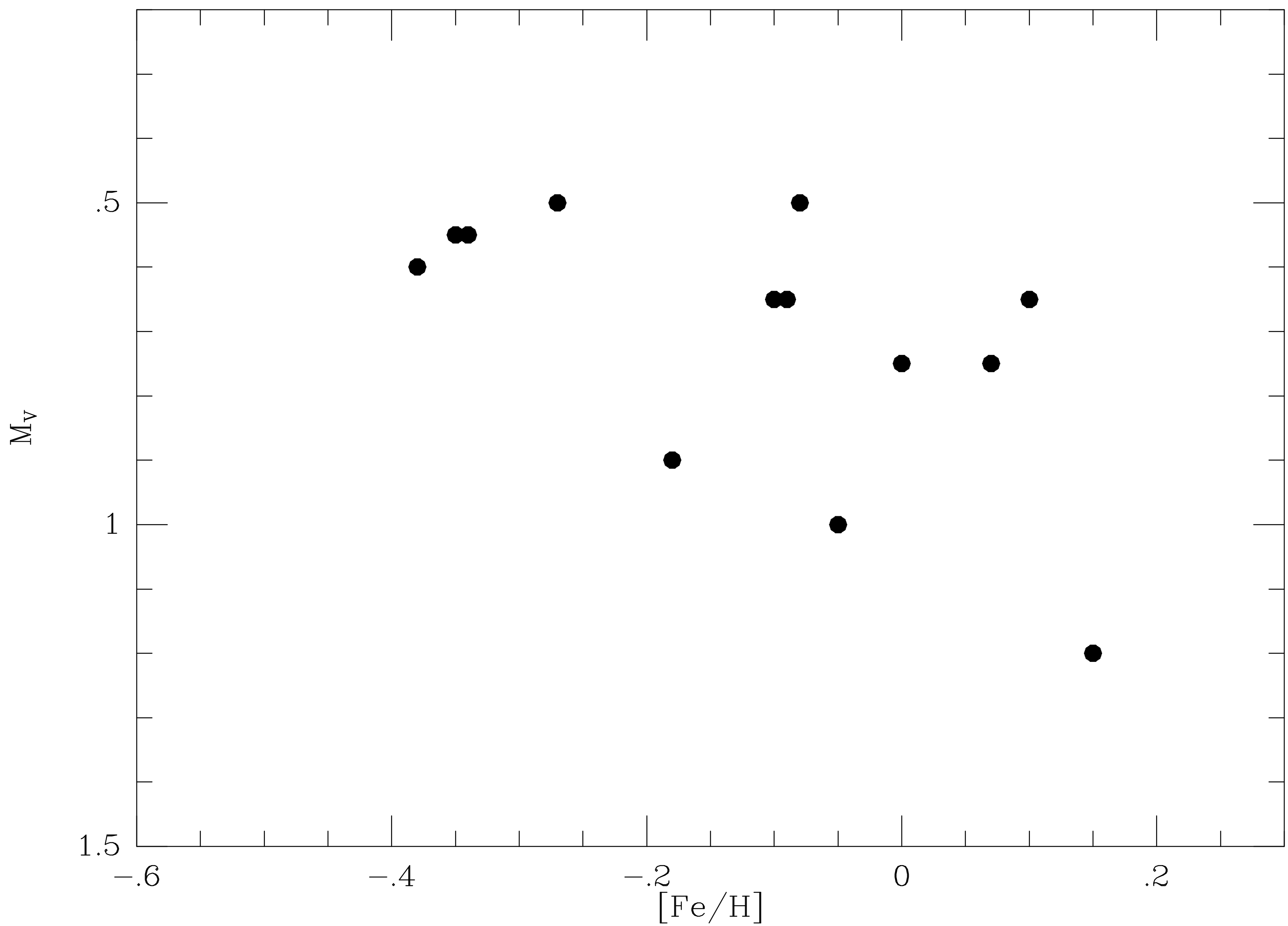
Fig. 3.— (a) Cluster abundances as a function of galactocentric position as given in Table 2. (b) Same as (a) without error bars. Open circles are rederived DDO abundances, open triangles are spectroscopic abundances, closed triangles are combined DDO and spectroscopic results, and open squares are transformed DDO abundances from unpublished photometry.

Fig. 4.— Absolute distance away from the galactic plane as a function of metallicity for the clusters used by PCA (open circles) and the additional sample of FJ (crosses).

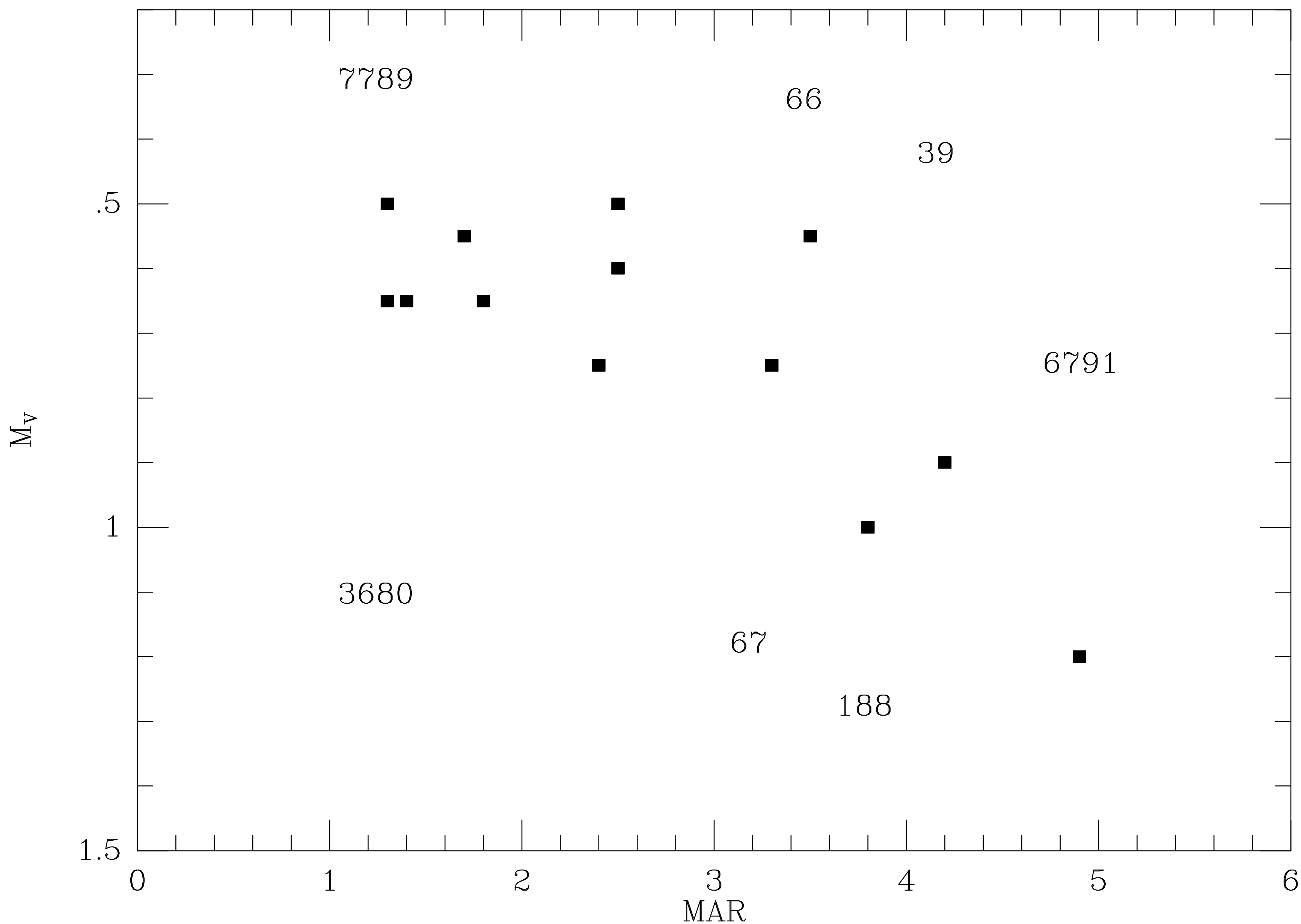
Fig. 5.— Absolute distance away from the plane as a function of galactocentric distance. Same symbols as Fig. 4.

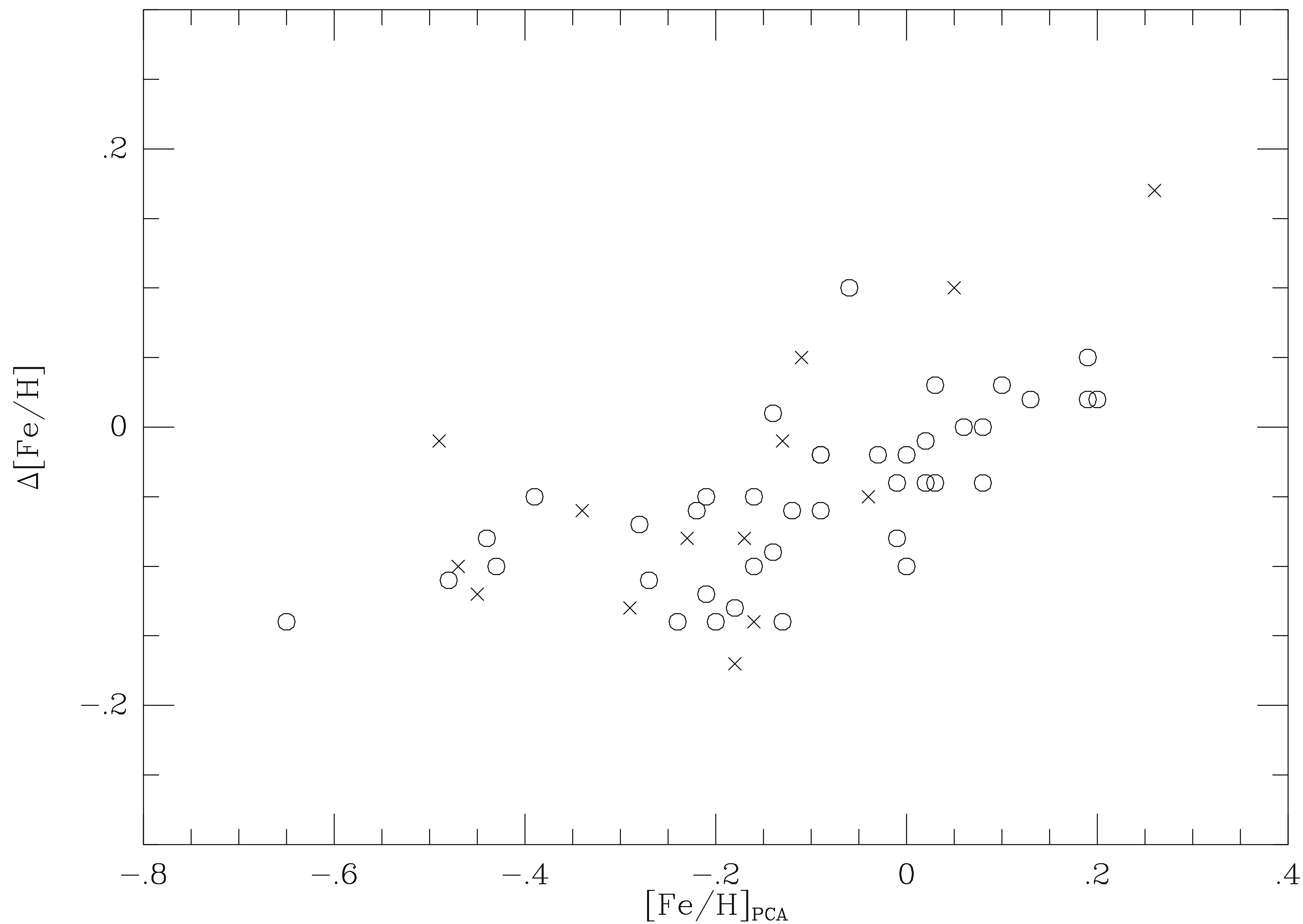
Fig. 6.— Same as Fig. 4 after adjusting the clusters beyond $R_{GC} = 10$ kpc for an offset in [Fe/H] of 0.32.

Fig. 7.— Metallicity distribution for field stars, Thin + Thick Disk (dashed curve), Thin Disk (dash-dot curve) from WG, and the inner clusters (solid curve). The first two histograms have been offset by 0.02 in [Fe/H] from the solid curve to make the curves more distinguishable.

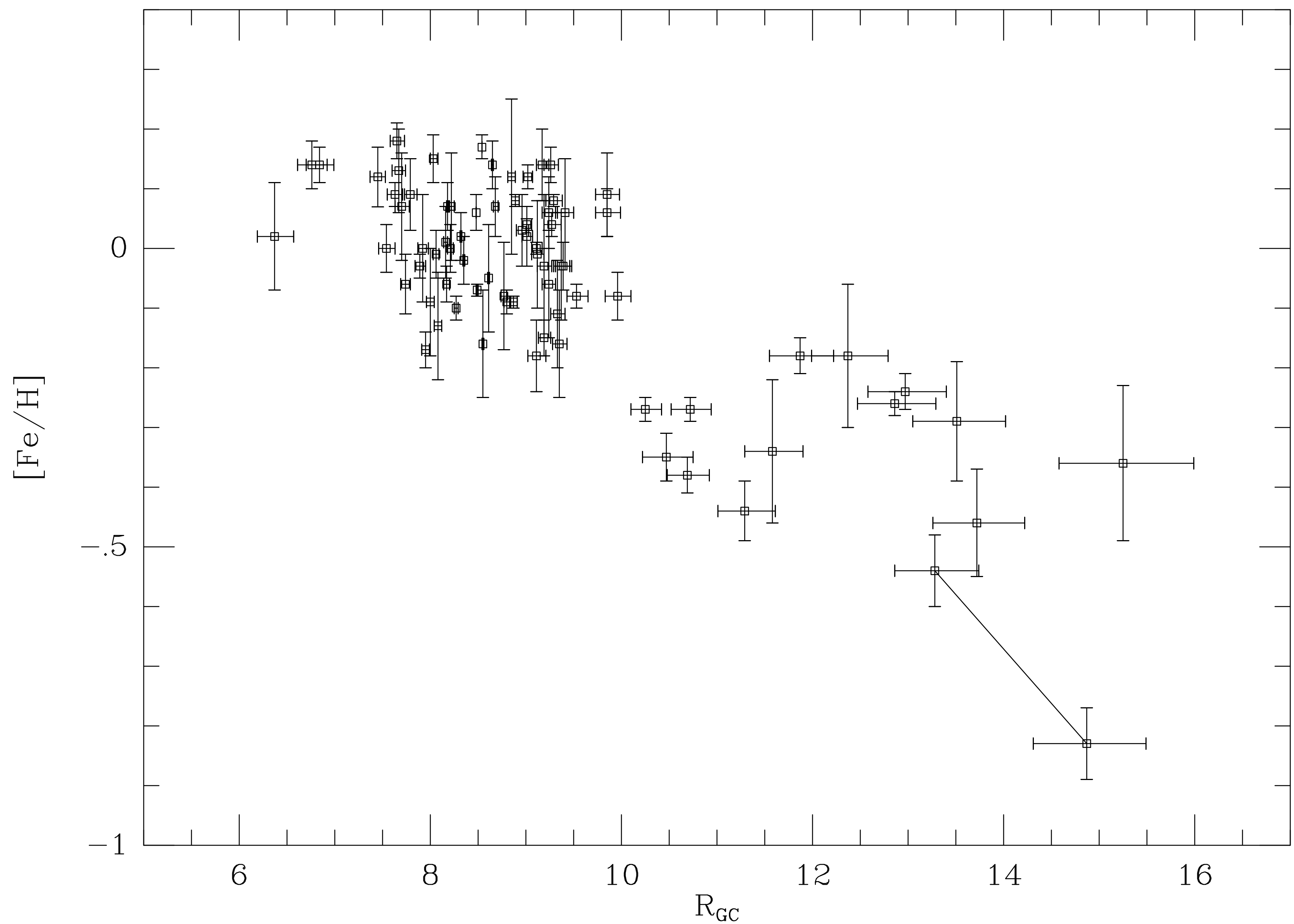


.5
1
1.5
−.6
−.4
−.2
0
.2
[Fe/H]
M_V

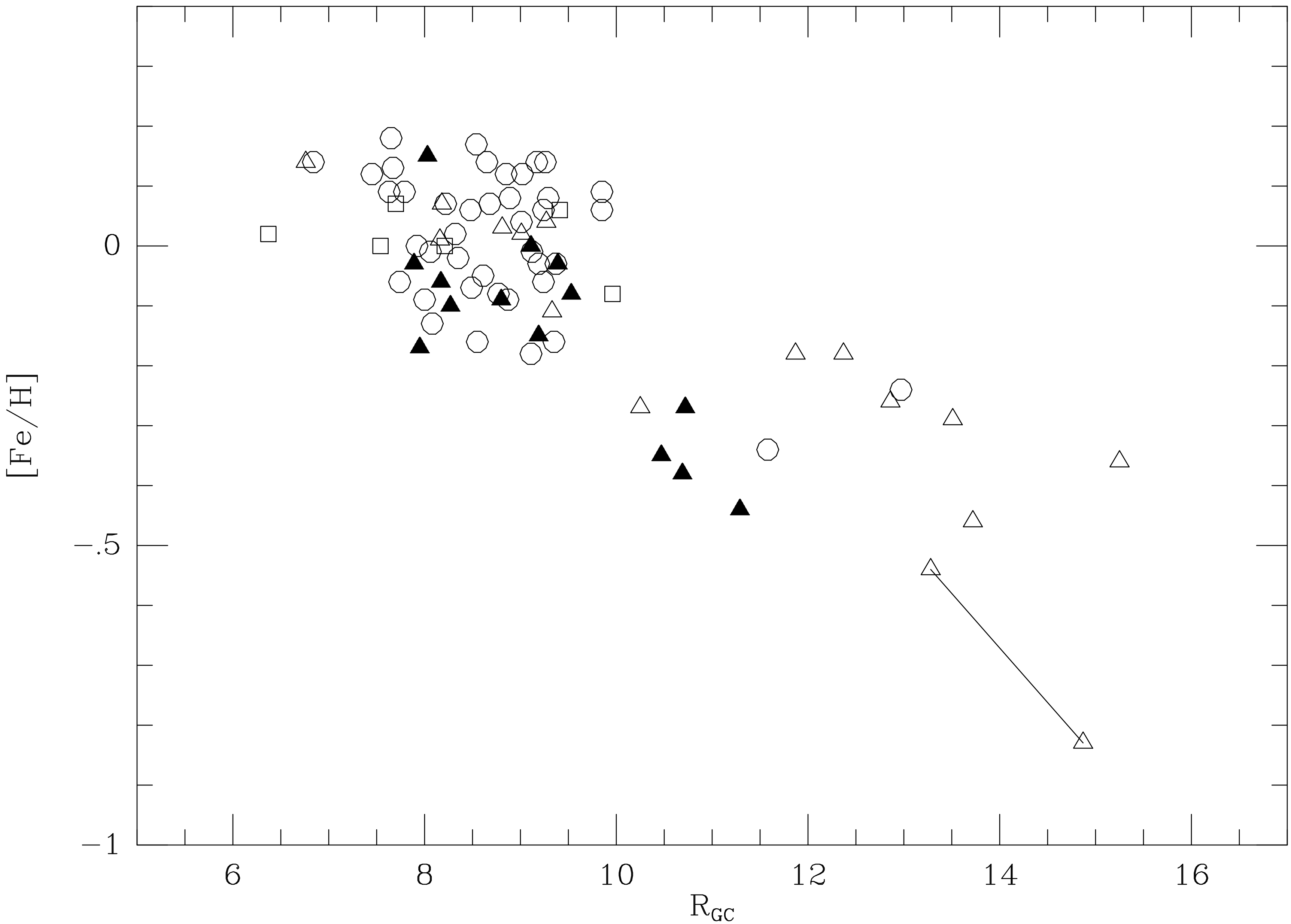

7789
66
39
6791
3680
67
188
.5
1
1.5
0
1
2
3
4
5
6
MAR
M_V



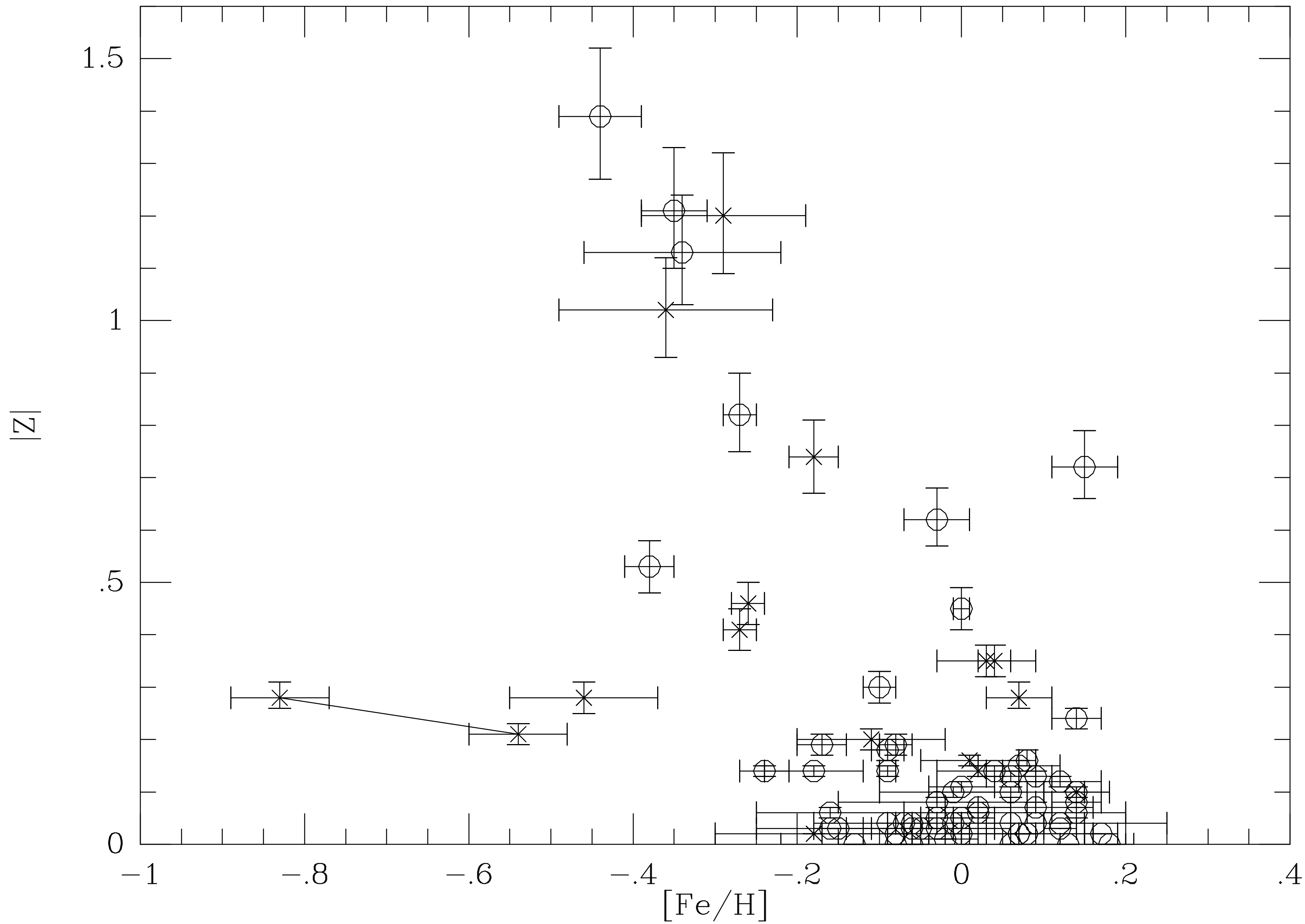
Δ[Fe/H]
.2
0
−.2
−.8
−.6
−.4
−.2
0
.2
.4
[Fe/H]PCA

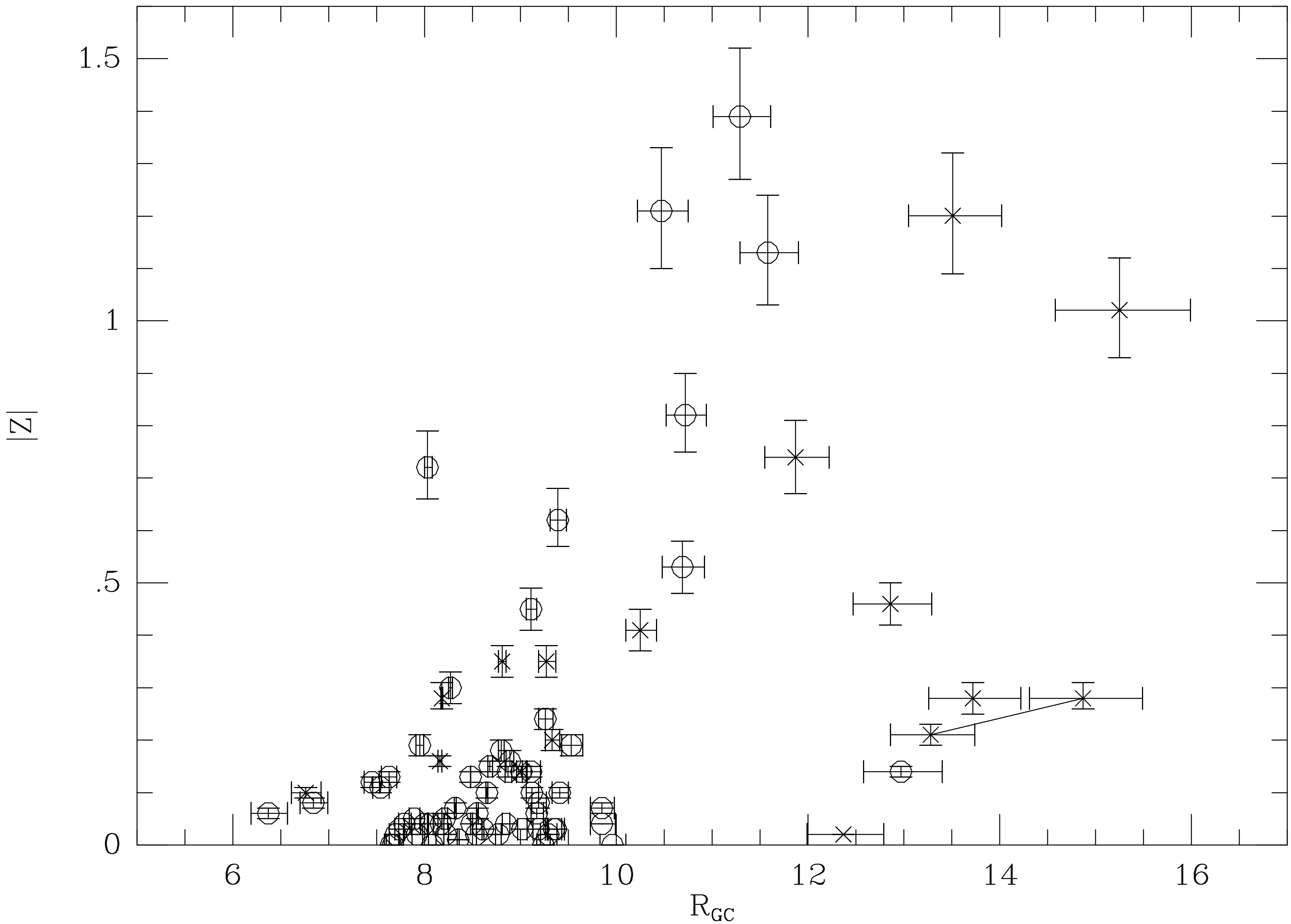


[Fe/H]
0
−.5
−1
6
8
10
12
14
16
R_{GC}



[Fe/H]
0
−.5
−1
6
8
10
12
14
16
R_{GC}


|Z|
1.5
1
.5
0
−1
−.8
−.6
−.4
−.2
0
.2
.4
[Fe/H]



|Z|
R_GC
0
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1
1.5
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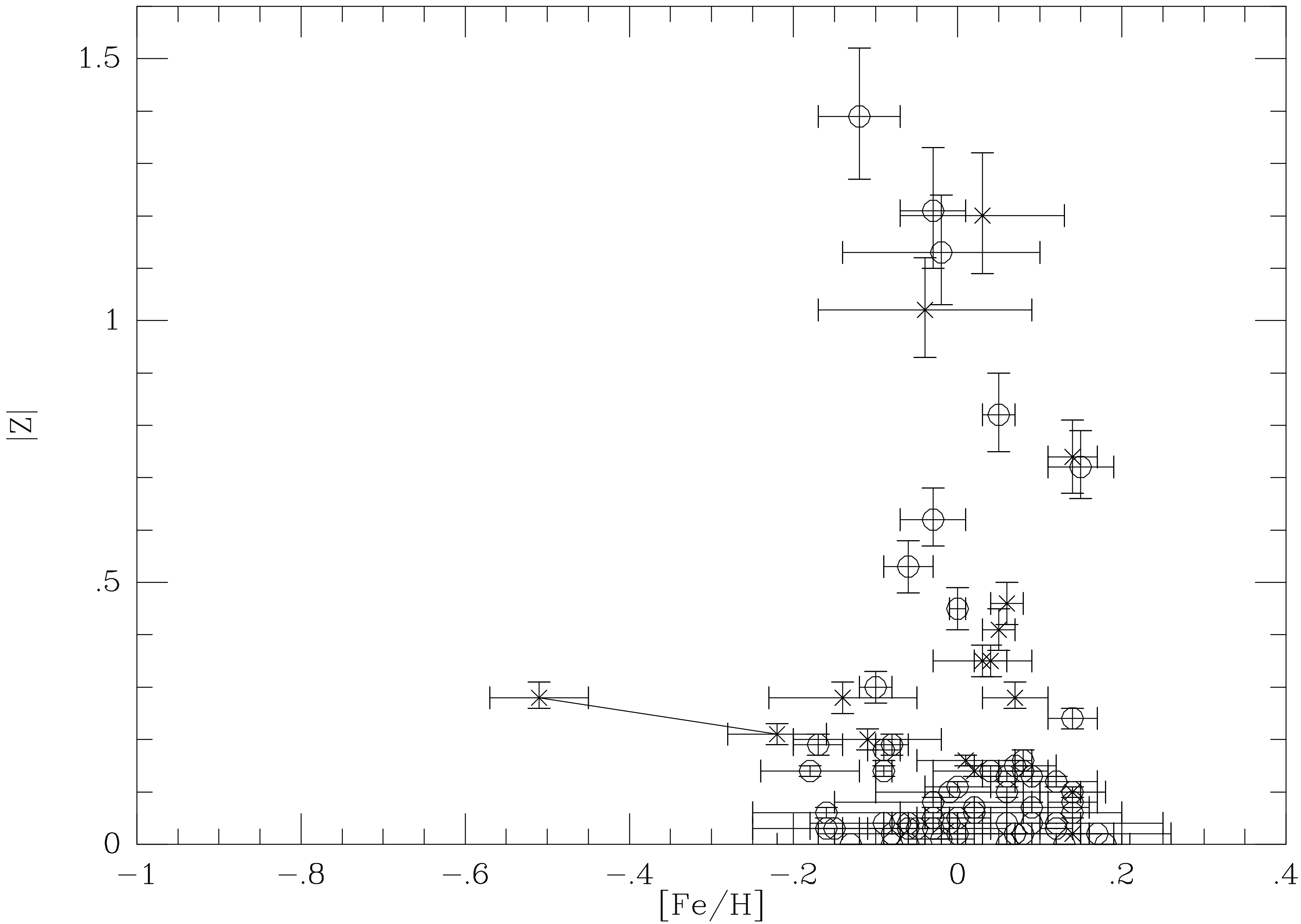
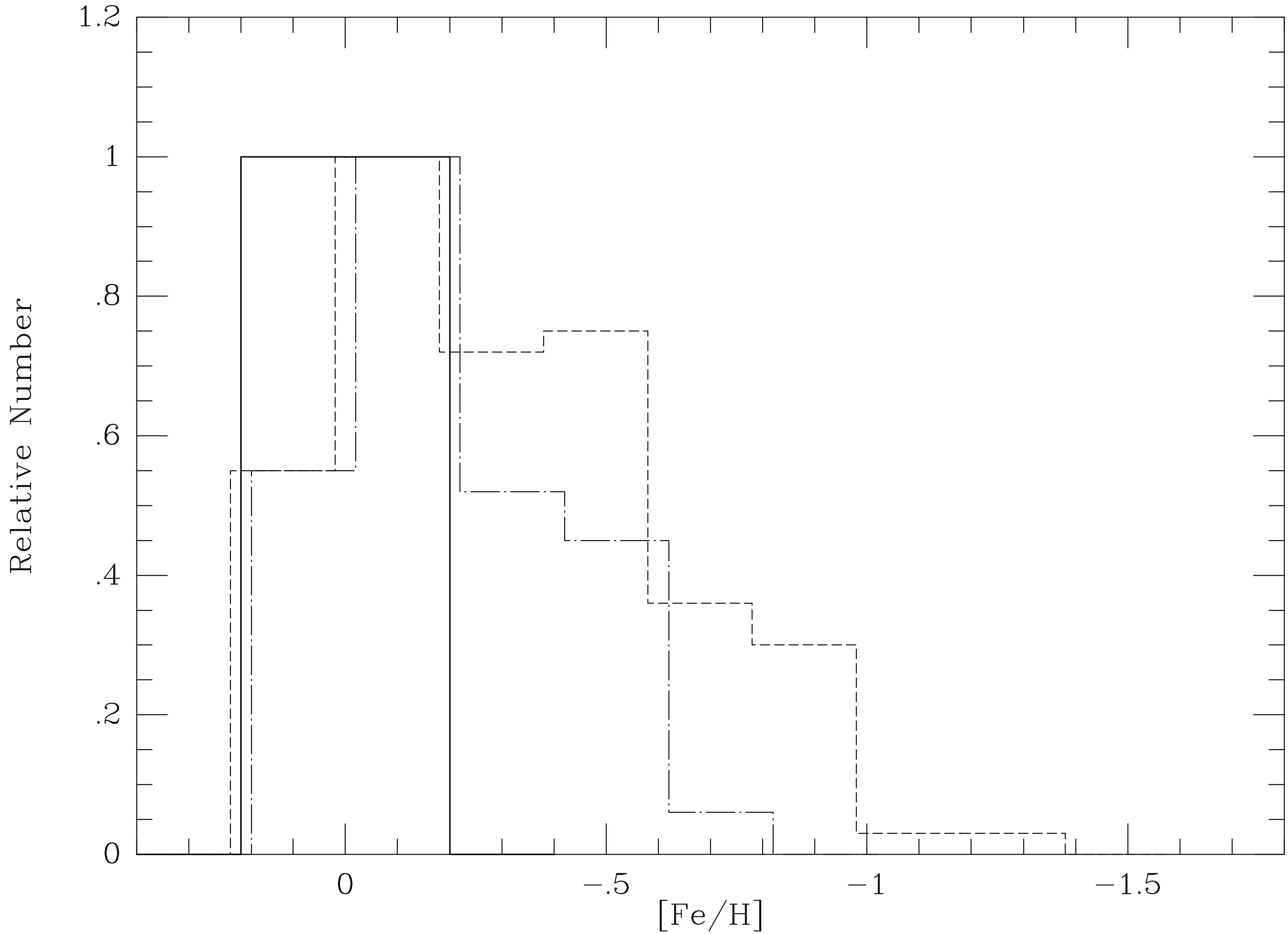
12
14
16



1.5
1
.5
0
|Z|
−1
−.8
−.6
−.4
−.2
0
.2
.4
[Fe/H]


1.2
1
.8
.6
.4
.2
0
Relative Number
0
−.5
−1
−1.5
[Fe/H]